Transactions of American Society for Steel Treating

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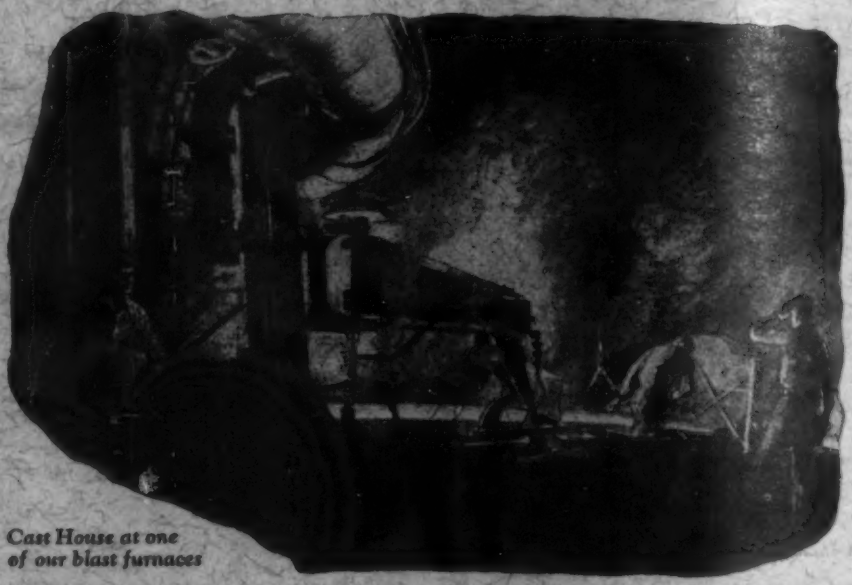

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TRANSACTIONS
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AIRCRAFT METALLURGY

By Horace C. Knerr

Abstract

This paper briefly outlines the metallurgy of aircraft manufacture, touching upon such features as choice of materials, specifications for purchase and inspection thereof, properties of the principal metals used, processes of machining, forming, rivetting, welding, brazing, foundry practice, and corrosion prevention, and discussing methods of metallurgical control. Some causes of failure and their prevention are set forth. An example is given of the results of the application of correct principles in reducing the rejection of metal parts during fabrication.

THE term "aircraft" refers to the various structures by means of which man is able to fly. These are of two classes, namely, heavier-than-air, including airplanes, sea planes, flying boats, etc., and lighter-than-air, including airships (dirigibles) both rigid and non-rigid, and other types of balloon.

The metallurgical requirements of the aircraft industry are exceptionally exacting, and are a stimulus to the development of improved processes and materials.

Beginning as it did, under the press of war emergency, evolution in the aircraft industry was rapid for a few years. Effectiveness for military purposes was the primary object. Cost was almost disregarded. Then followed a post war period of gradual but substantial progress, from an engineering standpoint, which is now giving way to an era of great development for civil purposes.

A paper presented before the ninth annual convention of the society held in Detroit, September 19 to 23, 1927. The author, H. C. Knerr, a member of the society, is consulting metallurgist, 538 E. Washington Lane, Philadelphia. Manuscript received July 14, 1927.

For commercial purposes, first costs and operating costs must be reduced to a minimum, while safety, reliability and performance are improved. The problem is therefore even more exacting than for military purposes.

Both military and civil aircraft call for the utmost in materials of construction and for skillful engineering, close attention to minute detail, and rigorously careful shop practice. Every ounce of weight must justify its existence or go, in order that the maximum useful load may be carried, therefore there can be no large "factor of ignorance" in design, yet the factor of safety must be adequate to cover all emergencies. The very best in materials, workmanship and engineering are ultimately the most economical, in aircraft, perhaps more than in any other product.

Evolution in Construction. Until after the close of the war, the principal material of construction for aircraft was wood. This was partly because wood is easily worked on a small scale, and also because improved alloy steels and aluminum alloys in forms and sizes suitable for aircraft, were not yet available. Moreover, various attempts to adopt metal construction failed because of incorrect engineering design. The use of metal has resulted in reduction in weight, increased strength, improved reliability, minimum hazard in crash or fire, and, (on a production basis) lower manufacturing costs. This has come about as the result of a better understanding of the properties of metals on the part of aircraft engineers, the development of improved methods of fabricating and joining metals and the production of new alloys of superior properties in suitable thin sections. Today, correct practice in the use of metals, to obtain their best value from a structural standpoint, is a determining factor in successful aircraft construction.

Engines a Separate Problem. Aircraft engines have, of course, always been of metal, and now represent one of the highest developments of the engineering and metallurgical arts, because of their amazing lightness, power, endurance, reliability and efficiency.

Early aircraft engines, of which the Liberty engine was outstanding, were of the water-cooled type, and represented an evolution of the automobile engine. Recent development has been toward the air-cooled engine, of the radial type, of which the Wright Whirlwind J 5 model is an admirable example.

Materials used in the Liberty engine are still typical of most

aircraft engines, except for the introduction of forged and cast aluminum alloys for certain parts, and the use of improved heat resisting alloys for valves and parts exposed to high temperatures.

Table I
Typical Materials in Liberty Engine

	Ten. Str., Lbs. Per Sq. In.	Y. P., Lbs. Per Sq. In.	Elon. in 2" %	Red. Area %
Parts requiring high strength, such as crankshafts, connecting rods, etc., 3½% nickel, chromium-nickel or chromium-vanadium steel having 0.30 to 0.40% carbon	175,000	150,000	12	40
Parts of medium strength, medium carbon forging steel S. A. E. 1035 or 1045	90,000	60,000	18	45
Parts of low strength, calling for deep forming, welding, etc., low carbon steel, S. A. E. 1010 to 1025	50,000	30,000	22	..
Crankcase, etc., aluminum alloy castings, copper 8%, aluminum remainder	18,000	.....	1.5	..
Pistons, copper 10%, aluminum remainder	18,000	.....	..	..

In the Wright engine, shown in Fig. 1, the crank case, cylinder jackets, pistons and certain other castings, are of heat treated high strength aluminum alloy known as "Y" metal, all foundry work and treatment being done at the plant. Little carbon steel is used except in the cylinder barrel forgings. Forged parts, such as the connecting rods, are of chromium-nickel steel (S. A. E. 3140), drop forged and finally machined after heat treatment. Chromium-nickel steel (S. A. E. 3115) is used extensively for case hardened parts.

Metallurgical practice for aircraft engines is necessarily of the highest type, but is, in general, analogous to that of automobile engines. The construction of aircraft engines is a subject and an industry fairly separate and distinct from the construction of the structural parts of aircraft,—namely, the fuselage or body, wings, rudders and stabilizers, landing gear, pontoons, floats, etc.,—to which attention will be principally directed in this paper.

Structural Metal Parts. Aircraft have many small parts of metal, such as bolts, eye bolts, terminals for wire stays and for struts, ends of wing beams (wing "hinges"), clevis pins, shackles, etc., (Fig. 2) nearly all of which are vital members carrying concentrated loads and high stresses. These are principally drop forgings, screw machine parts and "fittings," made up from sheet steel, seamless tubing, etc. Struts, wing beams and ribs, fuselage mem-

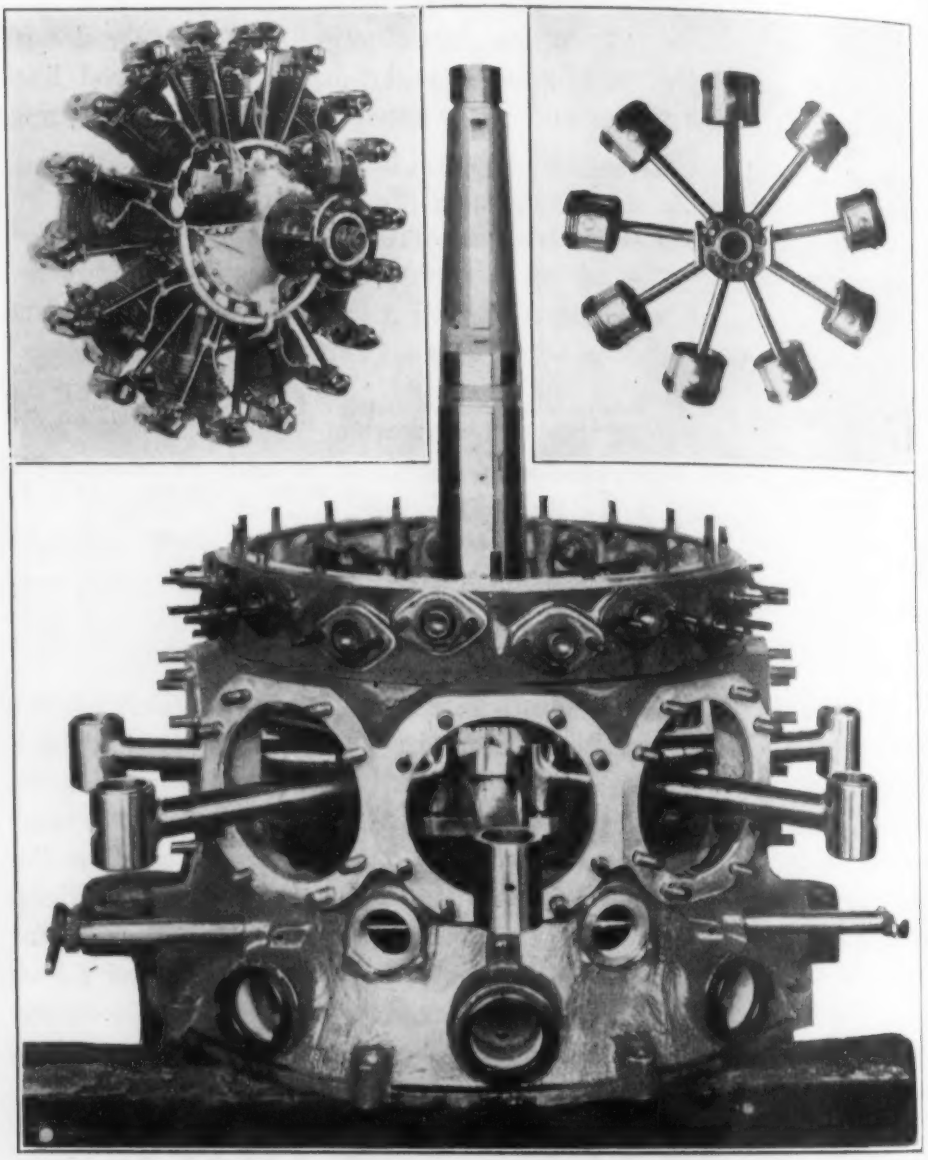


Fig. 1—Wright Whirlwind Engine, Model J5, Showing Crank Case Assembly. (Left Insert) Completely Assembled Engine. (Right Insert) Piston and Connecting Rod Assembly. *Courtesy Wright Aeronautical Corporation.*

bers, hulls of pontoons and boats, formerly of wood, and even in some cases, wing coverings of planes formerly of fabric, are being replaced by metal.

Structural Materials in General. At the time of the armistice, there was much confusion as to the materials used in aircraft. The Army and Navy, which were the only consumers, each had its own specifications and standards. These sometimes differed widely for

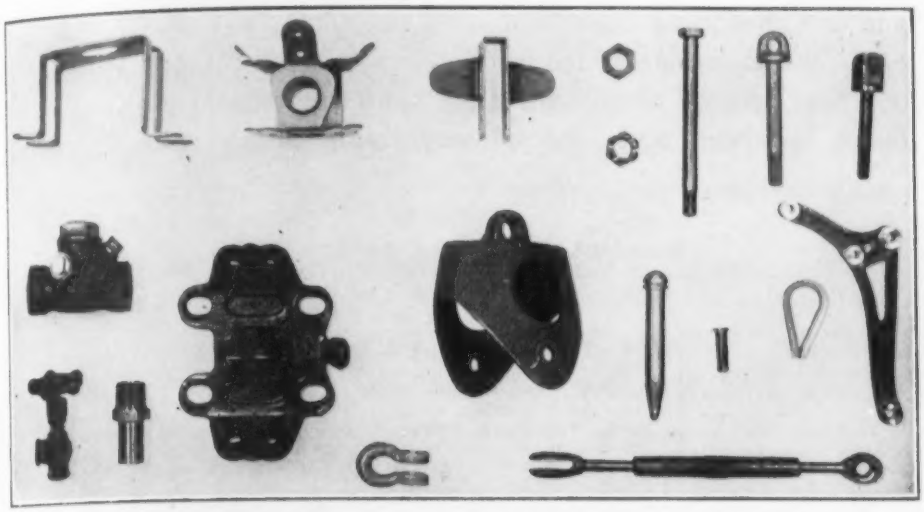


Fig. 2—Typical Small Metal Parts for Aircraft.

similar parts, and were occasionally crude, ambiguous, and not altogether sound. Steels were purchased principally on the basis of physical properties, a large variety of chemical compositions being allowed. This greatly complicated stock keeping and heat treatment. Alloy steels were used only in the form of bar stock and forgings, no satisfactory alloy steel sheet or seamless tubing being available.

No wrought or heat treated aluminum alloys were employed, although castings of the common 8 per cent copper-aluminum type were extensively used for crank cases and other slightly stressed parts of engines and planes.

Much copper and brass tubing was used, principally in oil, fuel and water lines, fittings being of cast brass. Tanks were of tin plate, terne plate, brass or copper sheet.

Simplification First Step. Beginning in 1923, periodic conferences were held between representatives of the Army, Navy and aircraft contractors, at which a program of simplification was conducted. New specifications were drawn up to follow progress in the art, including developments in aluminum alloys. The number of steels used for structural parts of aircraft was reduced from a possible several dozen down to the first six listed in Table II, the seventh, chromium-molybdenum, having been added recently.

New Materials

Steels. Among the materials adopted for aircraft use since the

war are chromium-vanadium steel sheet, 3½ per cent nickel and later chromium-molybdenum steel seamless tubing, duralumin and heat treated aluminum alloy sand castings of high strength. There has been some use of magnesium alloys. Stainless iron

Table II

Standard Army-Navy Aircraft Steels

Type	Steel No.	Purpose	Ult. Str. Lb. sq. in.	Y. P. Lb. sq. in.	Elon. in 2"
Mild Carbon	1025	Sheet, Bar and Tubing	55,000	36,000	22%
Medium Carbon	1035	Forgings only	80,000	60,000	22
Spring Steel	1095	Springs (also music wire)	.....	.....	..
3½% Nickel	2330	Bar and Tubing	125,000	100,000	12–17
Chromium-Vanadium	6130	Sheet	125,000	100,000	10
Chromium-Vanadium	6135	Bar	150,000	115,000	14
Chromium-Molybdenum	4130X	Seamless Tubing	95,000	60,000	12 or better

and some of the corrosion and flame-resisting steels are beginning to be used and have great promise for the future, especially in sea planes.

Principally because of its superior cold bending properties in the annealed state, coupled with otherwise satisfactory character-

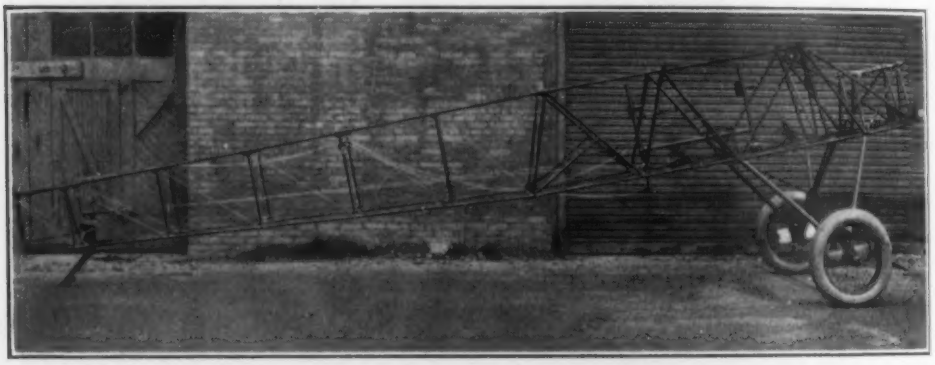


Fig. 3—Skeleton Fuselage Assembly on Landing Gear. Good Example of Steel Tube Construction, Showing Tension Members and Wire Stay Rods.
Courtesy Consolidated Aircraft Corporation.

istics, chromium-vanadium steel sheet was adopted for the manufacture of fittings requiring high strength. This steel was not found to draw well into the lighter sizes of seamless tubing, therefore 3½ per cent nickel steel was employed. The latter is now giving way to chromium-molybdenum steel tubing, which not only draws well, but has exceptionally good welding qualities, both for strength and soundness, and is being widely used for welded fuselage and wing structures which are not heat treated after welding.

One of the reasons for adoption of this steel is the excellence of its physical properties after welding and without subsequent heat treatment, the following values being counted upon in design:

Ultimate Strength	95,000 pounds per sq. in. (min.)
Yield Point	60,000 pounds per sq. in.
Elongation in 2 inches	12 per cent

This refers to the strength of the tubing at its weakest point, a short distance from the weld.

When normalized by heating to any temperature between 1500 and 1600 degrees Fahr., and allowed to cool with free circulation

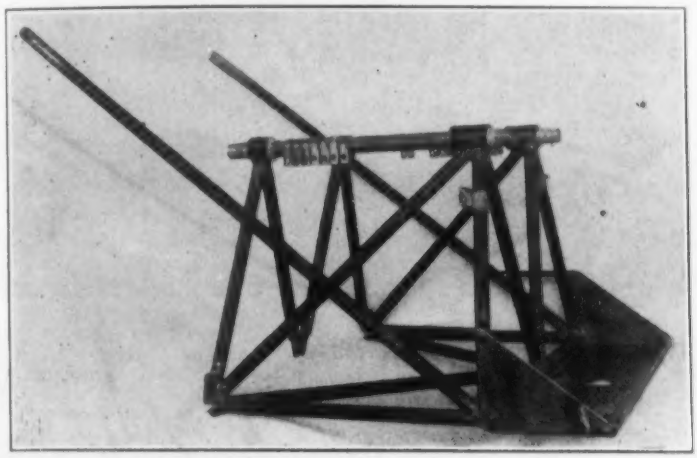


Fig. 4—Engine Mount Assembly Used on Plane Shown in Fig. 3.

of air, the following physical properties are obtained in tubes whose wall thickness does not exceed about $\frac{1}{8}$ inch:

Ultimate Strength	100,000 pounds per sq. in. (min.)
Yield Point	80,000 pounds per sq. in. (min.)
Elongation in 2 inches	15 per cent

Duralumin. Duralumin first came into important use in this country in the construction of the Shenandoah. Duralumin, and other wrought alloys of the duralumin type, in the form of sheet, strip, bar, drop forgings, seamless tube, rolled or extruded sections, rivets, etc., (Fig. 6) are finding a wide use in airplane and seaplane structural members, and also in such special locations as propellors, wing surfaces, pontoons and floats, hulls, fuel tanks, and the catapult launching cars used on shipboard.

Characteristic properties of these alloys are given in Table III.

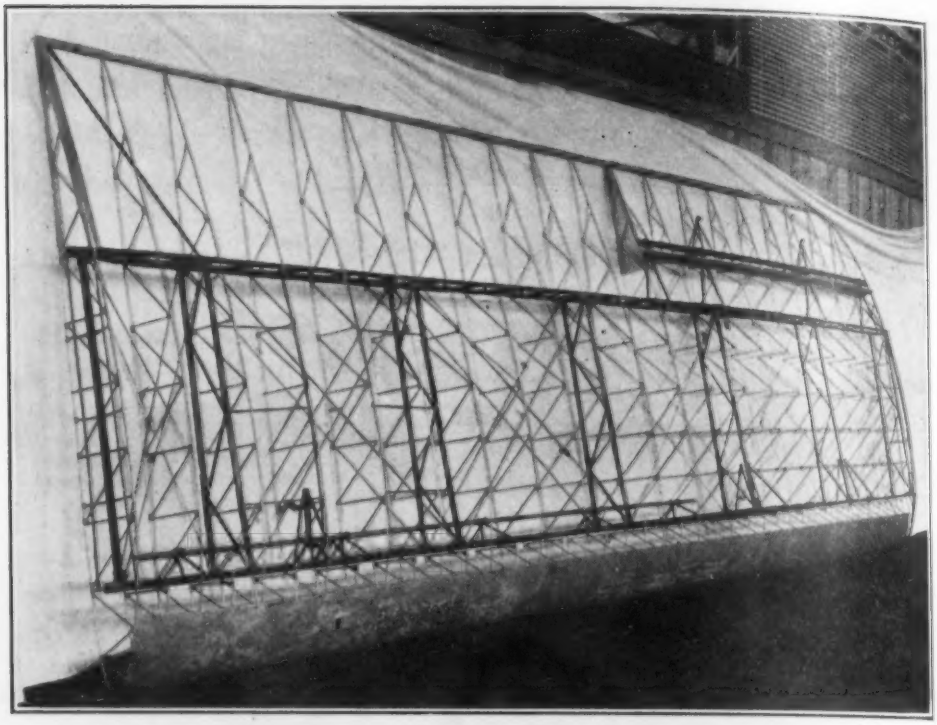


Fig. 5—Wing Frame of Large Bombardment Plane. Good Example of Efficient Metal Construction in the Large Planes. Struts and Spars are of Chromium-Molybdenum Steel Tubing, Welded. Ribs are of Duralumin Tubing Riveted, Sheet Duralumin Covering on Leading Edge. *Courtesy Keystone Aircraft Corporation.*

Aluminum Alloy Castings. Untreated aluminum alloy sand castings of the 8-per cent copper type, in combination with aluminum sheet and tube, have largely replaced the heavier metals formerly used in fuel and oil lines, the joints being made by gas welding. The first use of aluminum alloy castings of high strength came on the Shenandoah, where they were employed at junctions of beams, terminals or wire bracing, and in the fuel lines. They are now being used for certain moderately stressed members of airplanes, and in catapult cars for launching seaplanes from the decks of battleships. There is a wide variety of these alloys, most of them heat treated, and their individual properties adapt them for special uses. Characteristics of important aluminum casting alloys are given in Table IV. Nearly all of these are employed in aircraft. (Fig. 6.)

Magnesium Alloys. Magnesium alloys, both cast and wrought, have been used to some extent, for example as forged propellors, as cast pistons, and as extruded structural shapes, but their tendency toward corrosion is still a drawback, although much improvement

has recently been made in this respect. Typical characteristics are:

Composition—Aluminum 4 per cent., Magnesium, remainder.
Specific Gravity—1.7.
Weight—0.06 pounds per cubic inch.

	Cast	Extruded	or	Rolled
Ultimate Strength	25,000	34,000	to	40,000
Elongation	9 per cent	8	to	16 per cent

Table III

Characteristic Properties of Wrought Aluminum Alloys

	Composition per cent				
Type	Cu	Mn	Mg	Si	Aluminum (Min.)
Dural. or 17S	3.5–4.5	0.4–1.0	0.3–0.75	0.5 approx.*	92.00
Alloy 25S	3.9–5.0	0.5–1.1	.....	0.5–1.1	92.00
Alloy 51S	.....	.....	0.45–0.80	0.60–1.20	96.5

Type	Tensile Strength p. s. i.	Yield Point p. s. i.	Elong. % in 2"	Brinell 500 kg. 10 mm.	Condition
Dural. or 17S	25,000–35,000	7,000–10,000	14–22	45– 55	Annealed.
	55,000–63,000	30,000–40,000	18–25	90–105	Quenched and aged (Room temperature.
Alloy 25S	23,000–35,000	7,000–12,000	12–20	45– 55	Annealed.
	55,000–63,000	30,000–40,000	16–25	90–105	Quenched and aged at elevated temperature.
Alloy 51S	14,000–19,000	4,000– 6,000	22–32	25– 32	Annealed.
	45,000–50,000	30,000–40,000	10–18	90–100	Quenched and aged at elevated temperature.

NOTE—The mechanical properties of these alloys are influenced by the amount of hot working, cold working and rate of cooling in heat treatment. In material of thick section, the strength may be as much as 5,000 pounds per square inch lower.

*Present but not ordinarily specified.

Problems of the Metallurgist in Aircraft Production

Metallurgical problems to be solved in the production of aircraft, are diverse, and may be classified under the following headings:

A—Choice of materials and their correct use in design
B—Specifications for purchase
C—Inspection and test of raw materials
D—Storage and identification of stock
E—Fabrication,—
  1—Machining, punching, etc.
  2—Forming, hot or cold
  3—Joining—(a) Rivetting, (b) Welding, (c) Brazing, (d) Soldering
  4—Foundry practice
  5—Heat treatment
  6—Corrosion protection
F—Inspection during fabrication
G—Study of failures and defects to determine cause and prevent recurrence
H—Investigation of new materials and processes, to determine fitness for aircraft use.

Table IV

Aluminum-Base, Sand Casting Alloys

(Properties obtained from unmachined sand-cast specimens)

Alloy No.	Approximate composition	Ultimate tensile strength lbs. per sq. in.	Elongation per cent in 2 in.	Approx. yield pt. lbs. per sq. in.	Brinell Hardness (500 kg. 10 mm.)	Special characteristics
100	99% alum.	12,000-14,000	15-25	4,000	25	Too soft for structural purposes. Chemically resistant.
12 (S. A. E. No. 30)	8% copper	18,000-23,000	1-3	10,000	65	Common commercially, inexpensive, easy machining, readily welded.
112 (S. A. E. No. 33)	7.5% copper 1.5% zinc 1.2% iron	19,000-24,000	1-2.5	11,000	65	More brittle than No. 12, but easier to machine. Scrap may be used.
109	10-12% copper	19,000-26,000	0-1.5	15,000	70	Hard. Used for pistons, etc. Inexpensive, free machining.
43 (S. A. E. No. 35)	5% silicon	17,000-21,000	3-7	7,000	40	Good for thin or intricate castings requiring soundness. Good corrosion resistance.
45	10% silicon	19,000-23,000	1-3	9,000	50	Stronger, harder, less ductile and somewhat lighter than No. 43.
47[1]	13% silicon (modified)	25,000-30,000	5-10	11,000	60	Also known as Alpax. Affords high strength and ductility without heat treatment, but yield point is low, and machining difficult.
106	2% manganese	16,000-20,000	3.5-6.5	6,000	40	Good for fuel line fittings, etc. Fair corrosion resistance.
195[1] H. T.	4% copper	28,000-35,000	5.5-11	18,000	70	Best combination of strength and ductility for structural parts.
196[1] H. T.	5% copper	36,000-45,000	0-2.5	27,000	115	Superior hardness and strength to 195, but lower ductility.
145[1]	10% zinc 2.5% copper 1.2% iron	25,500-34,000	3-6	12,000	65	Good strength, ductility and shock resistance without heat treatment. Not resistant to corrosion. Softens rapidly at elevated temperatures. Some increase of strength and decrease of ductility with age.
"Y" H. T.	4% copper 2% Ni 1.5% Mg	32,000-36,000	1	25,000	90	High strength and hardness, but low ductility. Machining fair. Retains hardness and strength well at elevated temperatures (e. g., 600° F.). Used for air cooled engine parts.

NOTE: [1] = Patented. H. T. = Heat Treated.
Partly from "*Aluminum and Its Light Alloys.*" By Robt. L. Streeter and P. V. Faragher, *Mechanical Engineering*, May, 1925.

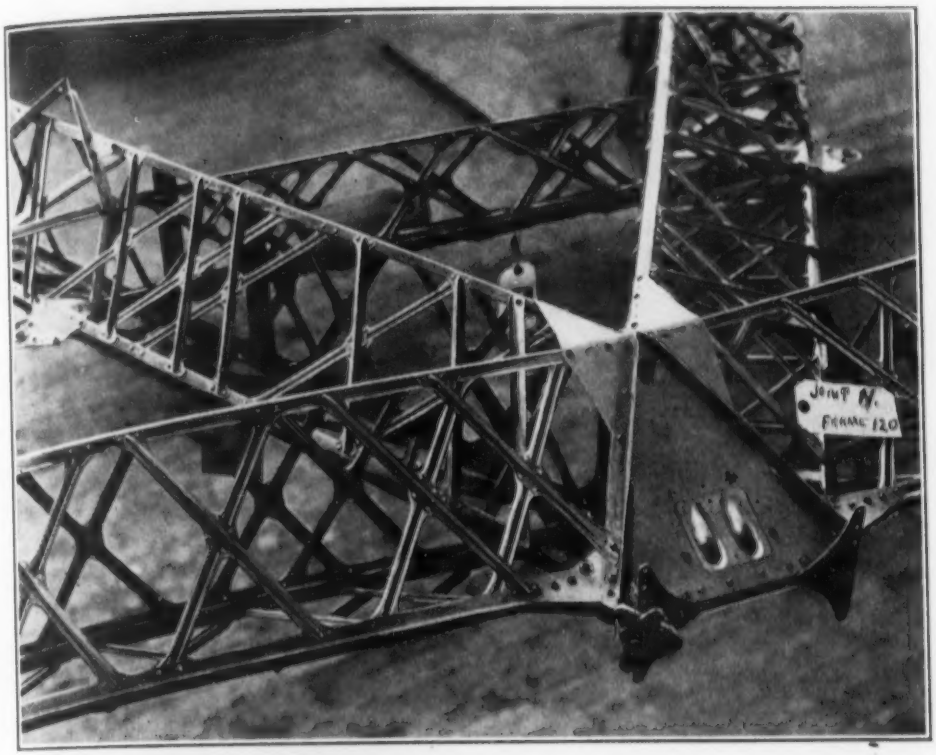


Fig. 6—Detail of Girder Joint in an Airship. Stamped Lattices Riveted to Rolled Channels, All Duralumin. Terminal Piece for Wire Stays, Aluminum Alloy Casting. Temporary Assembly Made with Small Bolts, Later Riveted.

Courtesy Naval Aircraft Factory, Philadelphia.

Choice of Materials. The correct choice of materials in the design of aircraft depends upon a number of factors, including the following:

1—Strength and weight. These two properties cannot be considered separately, since it is necessary to produce a structure of the required strength without exceeding a certain maximum allowable weight, and desirable to come as much under this weight as possible in order to increase the useful load. The strength-weight efficiency of structural materials may be compared on the basis of a "strength-weight factor", obtained by dividing the ultimate strength in thousands of pounds per square inch, by the specific gravity. Some typical strength-weight factors are given in Table V.

2—Availability. There should be a dependable and adequate source of supply.

3—Suitability to fabrication. Labor and overhead costs should not be excessive.

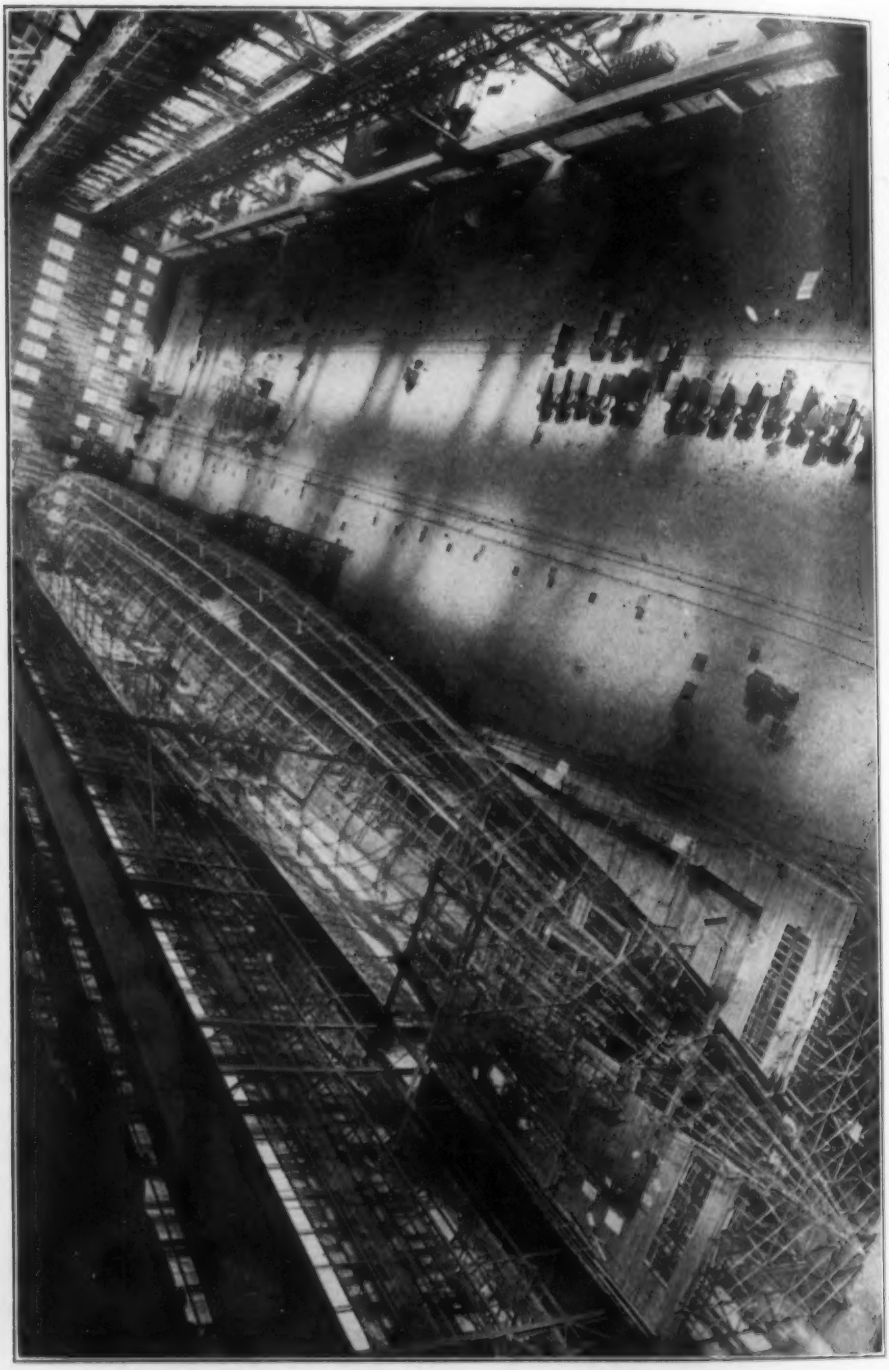


Fig. 7—Skeleton Structure of the Shenandoah During Erection at Lakehurst, N. J. *Courtesy Naval Air Station, Lakehurst, N. J.*

4—Permanence. Freedom from serious deterioration with time, exposure, change of climate, etc., within the expected life of the machine, should be assured.

5—Initial cost. This is usually of secondary importance in

comparison with the other factors, the cost of a finished airplane being around $10 per pound.

Correct Use in Design. Choice of materials and correct design to obtain to the best advantage the properties of those materials, are inseparably associated. Fabricating methods, heat treatment, etc., must also be such as to develop the desired characteristics.

Correct choice is often a matter of intelligent compromise or is determined by details of design. For example, duralumin and

Table V

Typical Strength-Weight Factors* of Aircraft Materials

			S. W. F.
Wrought Metals (Tension)			
Music wire—0.01-inch in dia.	400,000/7.85	=	51.
Alloy Steel—High	150,000/7.85	=	19.
Duralumin	55,000/2.85	=	19.
Magnesium Alloy	34,000/1.75	=	19.
Alloy Steel—Htd.	100,000/7.85	=	12.7
Mild Steel—Normalized	55,000/7.85	=	7.0
Aluminum—Annealed	12,000/2.7	=	4.4
Wood (Compression)			
Balsa	2,200/0.12	=	18.
Douglas Fir	6,000/0.54	=	11.
Spruce	4,300/0.43	=	10.
Oak, white	5,900/0.74	=	8.

*(Obtained by dividing ultimate strength in thousands of pounds per square inch, by specific gravity.)

alloy steel of 150,000 pounds per square inch have about the same strength-weight factor, but the greater thickness of duralumin for equal strength and weight render it preferable for parts where the extreme thinness of steel would be prohibitive.

For long columns and beams, in which flexure is the determining factor, square tube is stiffer than round tube of equal weight and equal diameter (across flats). This fact, although known to designing engineers, has for some reason been neglected until quite recently.

It has been found that, for certain locations, square tube with moderately rounded corners not only shows advantages in strength and lightness, but also affords savings in labor cost over round tubing, because of the greater simplicity in mitering joints and applying side loads. This case illustrates how careful study of details may decrease expense, while performance is improved. (Fig. 8.)

Specifications for Purchase. Ordinarily, both chemical composition and physical properties must be specified for metals, since neither one, alone, will insure satisfactory material.

The drafting of specifications calls for sound technical and

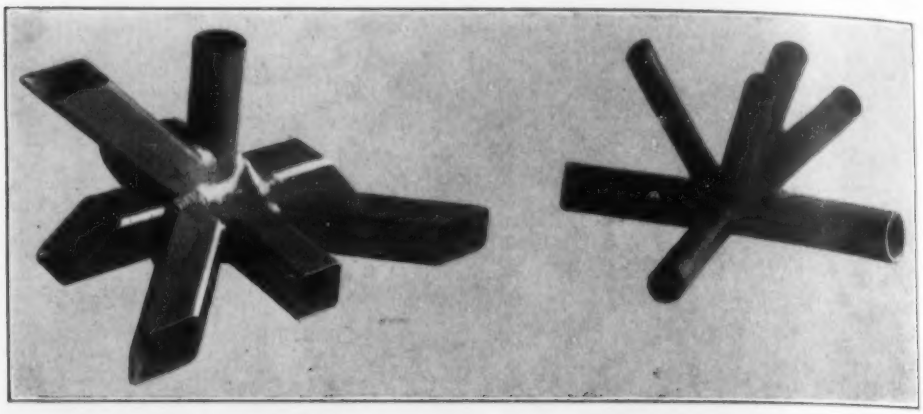


Fig. 8—Examples of Welded Joints in Airplane Construction. Showing Both Square and Round Tubing. *Courtesy Pitcairn Aviation, Inc.*

practical knowledge and for frank and friendly cooperation between manufacturer and user, each being more familiar with certain aspects of the problem than the other.

Government specifications have done much to advance the art of manufacture and make better materials commercially available. In many instances, manufacturers who at first complained of rigid requirements have ultimately brought their commercial product up to this standard.

Inspection and Test of Raw Materials

The commodity should be inspected and tested to determine whether or not it complies with the specifications.*

A serious difficulty always connected with specifications and their enforcement, lies in defining the limits of objectionable characteristics which are not readily measurable, such as surface finish, minor external or internal flaws, scale, "dirty" metal, etc. Here experience and judgment on the part of the inspector are called for.

*The private consumer sometimes lacks the facilities for conducting specified physical or chemical tests of materials, and therefore hestitates to purchase under specifications. In an effort to eliminate this difficulty, the U. S. Bureau of Standards is furthering the so-called "Certification Plan." Under this plan there is compiled a list of manufacturers who stand ready to supply material in accordance with selected specifications, and willing to certify to the purchaser that the material complies with those specifications. There is also compiled by the Bureau a list of commercial testing and research laboratories, which are prepared to conduct such tests and inspection as may be required.

Another difficulty is the determination of the number of specimens to be taken, under the sampling method, where samples are supposed to represent the whole. This depends partly upon the uniformity of a given lot of material, and upon the skill and care which have been applied in producing it. Sampling tests may often be supplemented to advantage by some form of test which can be applied to every piece or the entire body of material, to detect any variation beyond given safe limits. Such tests include hardness tests, proof tests in tension, bending or compression, qualitative chemical tests, magnetic analysis, X-ray inspection, and others.

Storage and Identification. Not only for safety but for economy and speed of production, material should be stored with scrupulous neatness and order. It is probable that more trouble arises through the confusion of metallic materials in storage or during the process of fabrication than through the delivery of unsatisfactory material by the supplier. Bar, sheet and tube stock should be marked with identifying color stripes over the full length, not merely at the ends. In case the stock of two or more types of steel have become mixed, they can sometimes be separated by simple metallurgical tests.

Fabrication

Machining, Punching, etc. The manufacture of aircraft still entails a large amount of hand work.

The production of "fittings" of more or less intricate design, from sheet steel, by cutting out, bending and joining blanks is one of the distinctive processes in aircraft construction. (Fig. 9).

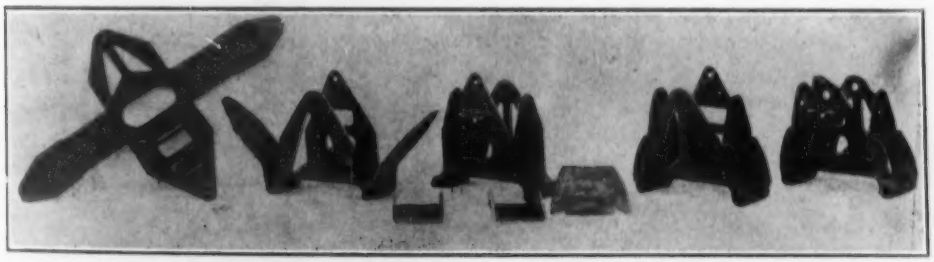
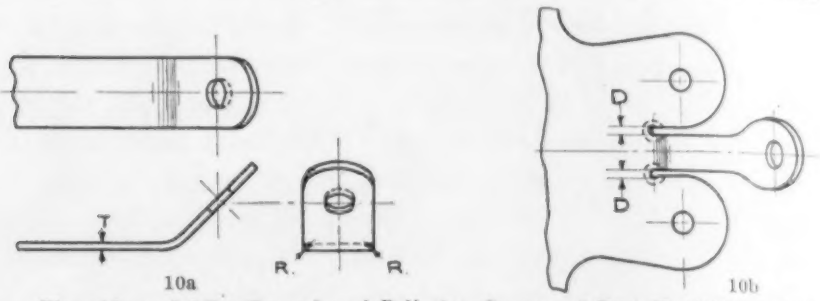


Fig. 9—Wing Hinge Fitting for Flying Boat Illustrating Progressive Stages in Forming Fittings from Sheet Metal, Welded and Brazed.

Blanks are usually cut in a nibbler or Gray cutter, in case production is insufficient to warrant punch press operations. For moderate production, as many as 500 to 5000 punchings have been made

from mild carbon and even alloy steel sheet, up to ¼ inch in thickness, by means of punches and dies made of commercial cold-rolled steel, cyanided on the cutting surface, at a moderate tool cost.

Among the advantages of aluminum alloys, either cast or



Figs. 10a and 10b—Examples of Relieving Corners of Bent Up Fittings to Avoid Cracking.

wrought, is low machining cost in comparison with steel or iron. This often offsets a higher initial cost as most of the cast alloys are easy to machine. Duralumin is readily cut with a metal cutting band saw.

Forming, Hot and Cold. It is very important to avoid incipient

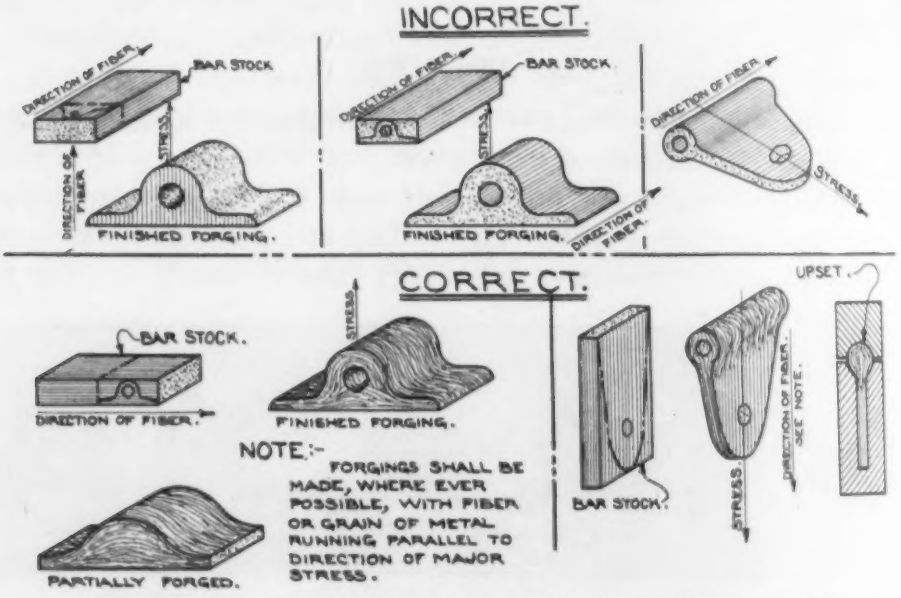


Fig. 11—Correct and Incorrect Directions of Grain or Fiber in Forgings.

cracks in bending sheet, for these spread in service. Sharp edges or re-entrant angles in the blanks should be avoided. Edges should be rounded by filing or grinding (parallel, not transversely) as in Fig.

10a, and saw cuts or notches relieved by drilling a small countersunk hole at the corner, as indicated in Fig. 10b.

In producing forgings, the aircraft manufacturer should take care that the "grain" or fiber of the metal runs parallel to the direction of major stress, to minimize the chance of failure in service. (Fig. 11)

Joining by Rivetting. In many respects, rivetting is the most satisfactory method for making permanent joints in metal parts of aircraft, since the strength is known with reasonable certainty, the surrounding metal is unaffected and heat treatment may be done either before or after assembly.

For duralumin, the rivetted joint is the only practicable one, except in certain cases which permit welding followed by a thorough

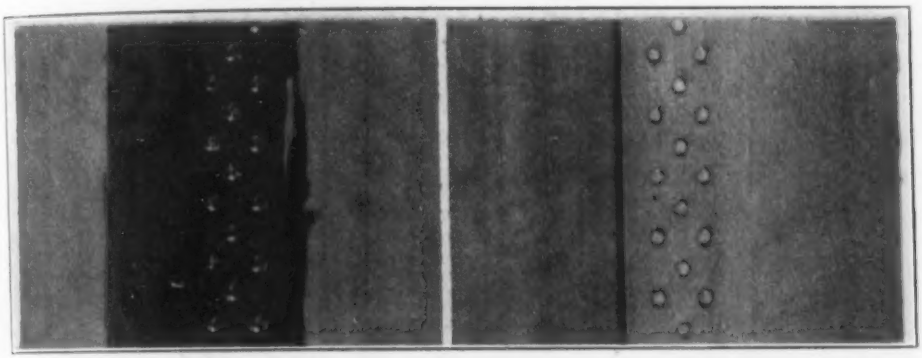


Fig. 12—Gas Tight Seam in 0.008-Inch Duralumin Sheet for Dirigible Covering. Rivets 0.035-Inch Duralumin. Front and Reverse Side of Joint. Note Penetration of Dope.
Courtesy Aircraft Development Corporation.

removal of all welding flux and heat treatment of the entire part. In assembling duralumin structures by rivetting, the rivets are heat treated immediately before driving (while still soft), after which natural aging developes their proper hardness and strength.

An ingenious and successful method of making joints in thin duralumin sheet, 0.008 inch thick, for the covering (gas container) of a rigid airship, as a substitute for balloon fabric, has been worked out by E. J. Hill, engineer of the Aircraft Development Corp. The metal covering contributes to the structural strength of the ship and the joints must be impervious to hydrogen gas. Welding being impracticable, the joints are "sewed" by means of three parallel rows of tiny rivets made of duralumin wire, 0.035 inch in diameter. After rivetting, by means of a special machine, the seam is sealed by painting with an asphaltum compound, which draws completely through it by capillarity. (Fig. 12)

Welding. The assembly of fuselage and wing structures by the acetylene welding of seamless steel tubing, has at this time, nearly replaced the earlier method of assembly by means of riveted joints and bolted fittings.

A properly made welded joint is ordinarily stronger than the adjacent metal. The method is inexpensive and convenient, but the results depend very largely upon the skill and conscientious care of the welder. Many aircraft assembled by welding, have been flying for long periods, with entirely satisfactory results. Records of failure due to defective welds are few. It may be assumed, therefore, that the method has earned a permanent place in aircraft construction. Nevertheless, the dangers to be avoided should be kept clearly in mind. There is at present no way of knowing the strength of any particular welded joint, except by proof loading, which is frequently impracticable and does not preclude fatigue failure. Surface inspection is undependable.

When fusion at a joint is not complete, a re-entrant angle or notch remains, which may develop into a progressive fracture under repeated stress. Welding sometimes causes cracks in the surrounding metal. Cracks on the *inside* of tubular longeron members, to which parts had been welded externally have been observed. These were not visible without splitting the tube open. The heat of welding tends to cause coarse crystallization in the weld and surrounding metal, inducing a tendency to weakness and brittleness. At some point near the weld, steel is heated to the spheroidizing temperature, which has the maximum annealing (softening) effect. Normalizing or quenching the entire member after welding restores the metal to a favorable condition, but cannot be applied to large structures.

In continuous thin, tubular members, transverse welds cause a shrinkage of about 1/32 inch per weld. In rigid structures this may set up dangerously high internal stresses. For example one such joint in a member 30 inches long, fixed at the ends, would produce a strain of 0.0012 inch per inch, and therefore a stress of 36,000 pounds per square inch, equivalent to the yield point of mild steel.

Crevices in welded members harbor moisture and electroplating or pickling solutions, favoring internal corrosion at vital points.

Electric arc welding has been used successfully by certain air-

craft manufacturers, but is open to about the same objections as acetylene welding.

Electric Spot Welding. Spot welding has been used to a great extent in assembling sheet steel fittings, especially in holding parts in place preparatory to gas welding or brazing. It is convenient, inexpensive and rapid, but a dangerous practice if misapplied, and has caused failures in service. The spot-weld creates a small brittle zone having a cavity in the center, and should therefore never be placed in the line of stress.

Welding Aluminum and Duralumin. The acetylene welding of aluminum has been quite successful and extensive, principally in the manufacture of fuel tanks. The most satisfactory method for sheet seems to be that of bending up the edges and melting together the flanges so formed, into a bead, without recourse to a filler rod. Success depends, among other things, upon the flux used. Aluminum welding fluxes are strongly corrosive, and must be removed thoroughly after welding. In the design of welded structures, provision must be made for the high thermal expansion of aluminum, by means of beads rolled in the metal, or otherwise.

The welding of duralumin is similar to that of aluminum, but more exacting. The metal is tender while hot and will crack alongside the weld unless cooling stresses are avoided. Duralumin should be heat treated after welding, in order to prevent a tendency to localized corrosion adjacent to the weld, and to increase the strength of the metal. This may be done by cooling in air from the quenching temperature, which, for thin material, imparts nearly as good properties as water quenching. Welded duralumin fuel tanks have been produced in this manner.

Brazing. Brazing may be done by means of the acetylene torch, a gas or oil flame, or by dipping. Torch brazing is convenient and much used but is likely to produce cracks, possibly due to intercrystalline penetration of brazing material at high temperatures. A flame of illuminating gas or a light oil is preferable, being milder and producing a less concentrated heat, and is ideal for work which cannot be dipped. When steel surfaces are properly cleaned and are close together, an excellent flow of brass occurs by capillarity.

Dip brazing is preferable whenever applicable. Brass covered with a layer of flux, is melted in a clay or graphite pot. The

properly cleaned and preheated parts are immersed in the brass, held long enough to insure penetration, removed and allowed to cool. Preheating should be gradual and uniform to prevent warping or cracking, and should not cause scale. This may be accomplished by heating the part first in an oven to about 800 degrees Fahr., then placing it in a pot of molten flux at about 1400 degrees Fahr., after which it is transferred to a second flux pot at 1600 to 1650 degrees Fahr., and finally to the brazing pot.

Dip brazing leaves mild steel in a normalized or pearlitic condition, depending on the rate of cooling. Where this condition is satisfactory, brass of 60 per cent copper, 40 per cent zinc, should be used and the brazing temperature should be about 1700 to 1750 degrees Fahr. If it is desired to heat treat the steel after brazing, the copper content of the brass should be 70 per cent, and the brazing temperature 1825 to 1875 degrees Fahr. This brass will permit the parts to be heat treated at as high a temperature as 1650 degrees Fahr. The brazed joint does not suffer by the treatment, but is improved. Flux should consist of a mixture of borax and boric acid, in approximately equal parts.

Properly brazed joints have a tensile strength of about 40,000 pounds per square inch. Dip brazing, especially, is an excellent protection against corrosion, as all crevices are filled. The steel is not overheated and embrittled as it is in welding, but is rather improved. After brazing, excess brass should be completely removed to permit inspection for possible cracks caused by careless preheating or handling. This may be done effectively and cheaply by means of an electrolytic stripping bath.

Soldering. Soft solder is used for brass and copper work and for steel cable and wire terminals, but all of these are finding less application in aircraft than formerly. Many solders for aluminum are available, but all are subject to disintegration on prolonged exposure to moisture.

Foundry Practice

The foundry requirements of the aircraft industry are restricted principally to aluminum alloy castings. In engine manufacture, and occasionally in planes, some brass and bronze castings are called for. The essential factors in the production of satisfactory aluminum alloy castings are—

(a) Use of suitable raw materials, including ingot, scrap cast-

ings and scrap sheet or other wrought stock. These should be clean and free from excessive impurities or inclusions, either metallic, nonmetallic or gaseous. Both scrap castings and ingot metal frequently contain the latter in such quantities that non-porous castings cannot be made from them. Nonmetallic inclusions, such as sand, pebbles, etc., and certain metallic impurities, such as iron, interfere with machining, causing hard spots. Practically all impurities detract from the physical properties. The writer has found scrap aluminum sheet, bar and tubing of the commercially pure (99 per cent) grade, highly satisfactory as a raw material, the required copper or nickel being added in the same form.

(b) Melting should be done in an iron or steel pot, using oil or gas fuel or electric heat, the metal being protected from the products of combustion.

(c) To obtain maximum physical properties, minimum porosity, and avoid the picking up of iron from the pot, melting temperatures should be constantly regulated by means of a pyrometer and preferably not allowed to exceed 1375 or 1400 degrees Fahr. at any time.

(d) Alloying metals, such as copper, nickel, or magnesium, should be in thin section and dissolved in the bath, not melted.

(e) The bath should be stirred sufficiently to insure thorough diffusion of alloying elements, and then allowed a settling period, so that inclusions or dross may settle or rise to the surface, after which the bath is carefully skimmed but not further stirred before pouring. The advantages of fluxing are questionable.

(f) Slight porosity, in fuel line fittings, or the like, may be cured by impregnation with sodium silicate, in a suitable container, first maintaining a vacuum and then applying the liquid under pressure.

Heat Treatment

Steel. Standardization on a minimum number of steels which will satisfactorily meet design requirements, not only simplifies purchase, inspection and stock keeping, but greatly reduces the problems of heat treatment in the shop. Detailed specifications should be prepared for the heat treatment of each type of steel, or the heat treatment of parts having different physical requirements although made of the same steel. A typical specification is as follows:

Heat Treatment Specification
Chromium-Vanadium Sheet Steel S. A. E. 6130

1—When work is inserted, temperature of furnace shall not exceed 1200 degrees Fahr. (650 degrees Cent.). Raise temperature gradually to 1600-1625 degrees Fahr. (870-885 degrees Cent.). Hold for 20 minutes.
2—Remove work and immediately quench in oil, with vigorous agitation.
3—After quenching, Brinell hardness should be between 300 and 475.
4—Temper for 30 minutes at a temperature determined by the hardness after quenching, as follows:—

Brinell	Tempering
300-350	800 degrees Fahr. (425 degrees Cent.)
350-400	850 degrees Fahr. (455 degrees Cent.)
400-475	900 degrees Fahr. (485 degrees Cent.)

5—After tempering, allow work to cool freely in air.
6—Physical properties required after tempering:—

Brinell Hardness.....	250-300
Tensile Strength.....	125,000 pounds per square inch, minimum
Yield Point	100,000 pounds per square inch minimum
Elongation in 2 inches	10% (at thickness of ¼-inch)

Hardness tests should be applied, preferably to all pieces, after heat treatment, to insure that they have responded properly.

Variations of composition within the specified chemical tolerance of standard S. A. E. steels, as well as variations in thickness or section, will cause pronounced differences in hardness, in parts made from a given steel. Such irregularities may be overcome by suitably varying the tempering temperature. After quenching, therefore, hardness tests should be applied, and the tempering temperature fixed accordingly, the correct values having been previously determined by experiment.

Long, straight members, such as axles, struts, wing beams, etc., may, in the writer's experience, be heat treated satisfactorily only in a vertical furnace in which they are suspended from the top and quenched by lowering into a tank placed directly beneath.

An inspector, whose interests are confined solely to quality of product, as distinguished from quantity or cost, should examine all parts after heat treatment, to determine whether they are within specified hardness limits, and to detect any physical imperfections such as cracks, warping or excessive scale.

The inspector should keep a daily log of all parts heat treated and should immediately report to the metallurgist any failures, defects or irregularities occurring in heat treatment, so that the metallurgist may at once investigate the circumstances while all evidence is at hand, in order to determine the cause, locate responsibility and prevent recurrence of the difficulty.

A record of the failure, and its cause and remedy should be made on a suitable form, and filed for reference.

Wrought Aluminum Alloys. The theory and practice of the heat treatment of duralumin and other aluminum alloys is comparatively new in the art, and presents some features differing widely from those of steel. Duralumin is heated to approximately 930 degrees Fahr. (500 degrees Cent.), held a suitable time and quenched in water, after which it is soft, but hardens and attains its maximum strength after about four days "aging" at room temperature. Certain similar alloys remain soft until artificially "aged" by heating to moderate temperatures.

Heating may be in an electric or fuel-fired muffle furnace, or in a bath of molten sodium nitrate. Temperature must be closely controlled; if too low, the best physical properties will not be developed, while if too high, the material will be spoiled. Heating in a nitrate bath is rapid, gives high output in a small space, and assures temperature uniformity when free circulation of the bath takes place, as it should. There is a certain danger from spattering of the salts, and of explosion if they come into contact with carbonaceous materials, while hot.

Ordinary steel treating furnaces may be used for aluminum alloys, provided satisfactory temperature control and uniformity are obtained. An electric muffle furnace in which forced circulation of the atmosphere is produced by means of a fan or blower, is excellent.

Bulky structures, such as duralumin tanks, which do not permit quenching by immersion, may be heat treated in an electric muffle furnace and cooled in air. See Fig. 13. The physical properties obtained in parts of thin section by "air quenching" are only slightly inferior to those obtained by water quenching, but the resistance to corrosion is much inferior. (Fig. 14) Aluminum alloys are soft and tender at heat treating temperatures and must be carefully supported and handled.

Castings. Aluminum alloy castings of high strength, require, in general, a protracted period of heating at temperatures in the neighborhood of 950 degrees Fahr., followed by quenching in water and aging at moderate temperatures. Heating for quenching should be in an air atmosphere, salts having been found injurious. An electric furnace for heating and aging is excellent. Steam may

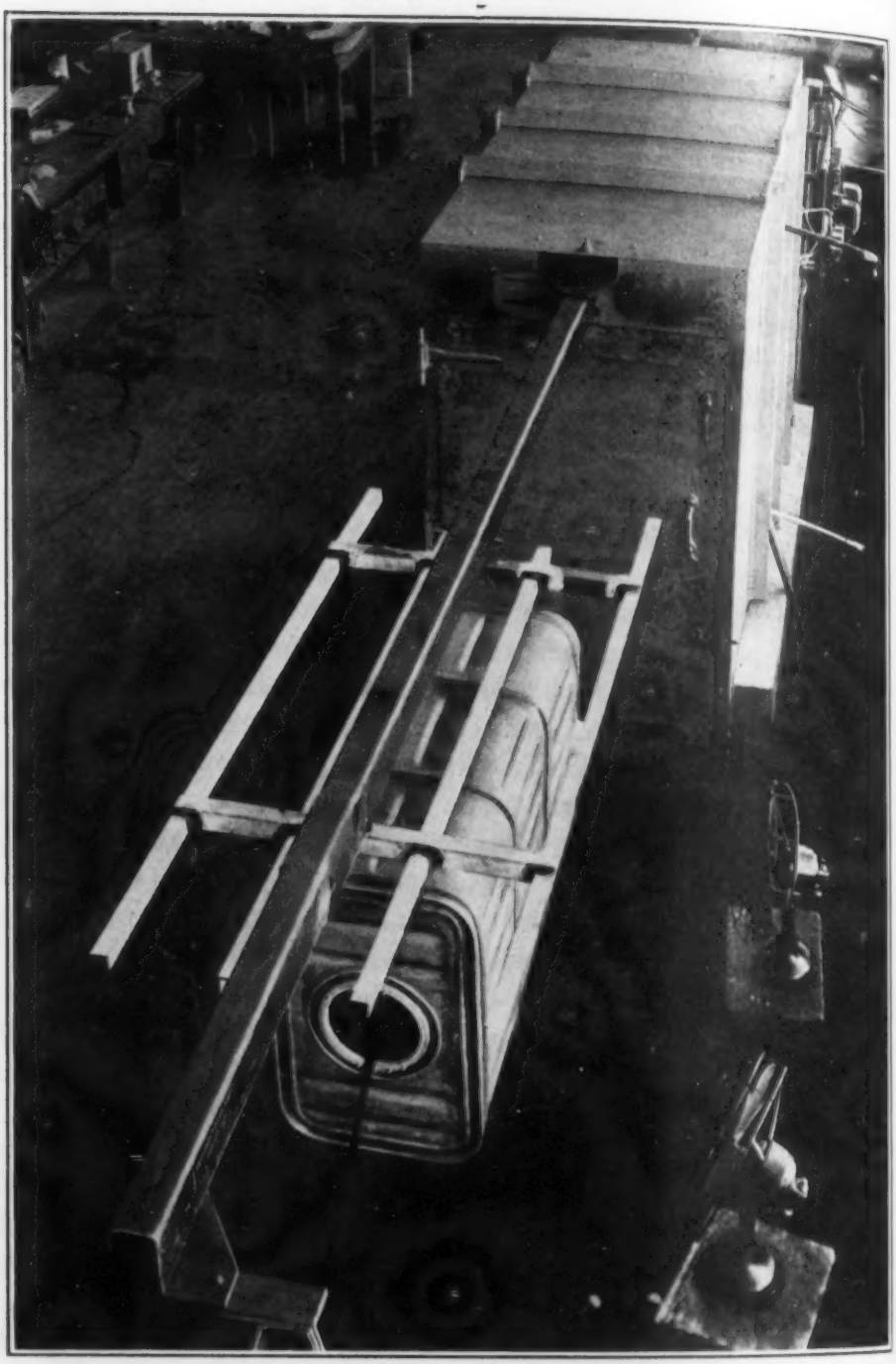


Fig. 13—Welded Duralumin Fuel Tank and Electric Oven and Fans for Air Quenching. Constructed at the Naval Aircraft Factory, Philadelphia.

also be employed for aging. Accurate temperature control is essential.

Corrosion Protection

Structural members of aircraft carrying high stresses are usually of thin section (often as thin as 0.035 inch or less), therefore it is important that deterioration by corrosion be prevented. Corrosive attack is especially active near salt water. For steel parts, a coating of zinc a few thousandths of an inch thick, applied by electroplating, is excellent. A satisfactory zinc coating should withstand continuous exposure to a spray of salt water (under specified conditions) for a period of 100 hours, without the appearance of rust. Electroplating with cadmium to a thickness of only a few ten thousandths, has given even better results than zinc plating, and does not interfere with thread tolerances.

Nickel plating and other common metallic coatings are without merit.

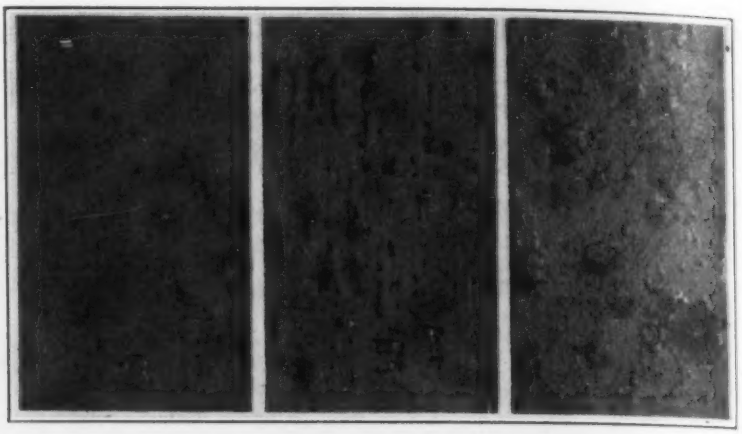
No form of electroplating has as yet been found entirely satisfactory as a protection for aluminum or its alloys because of a tendency to pit and peel off when exposed to moisture.

Aluminum enamel, consisting of spar varnish with a pigment of aluminum powder, is an excellent protection for steel or aluminum alloys, and in fact for nearly all types of aircraft materials. It may be applied over electroplated surfaces.

The protection of internal metal surfaces, such as the inside of tubular members and the adjacent surfaces of welded fittings, has long been, and still is, a serious problem in aircraft construction. In spite of efforts to hermetically seal by welding or otherwise, moisture is almost certain to reach the interior of cavities by condensation from the atmosphere. It is then retained there, and may cause almost complete loss of strength by corrosion from the inside, while the member still presents a perfectly sound appearance.

The most satisfactory method of internal protection for tubular members, so far devised, seems to be by the introduction of some form of adherent waterproofing material after assembly.

Aluminum alloys of thin section must be very carefully protected against corrosion. These are readily attacked by moisture which remains in contact for a considerable period, although when application is intermittent followed by thorough drying, they are rather resistant, due, perhaps, to the formation of a protective coating of oxide.



A C E

Fig. 14—Influence of Quenching Speed on Physical Properties and Corrosion of Duralumin. Duralumin, Quenched as Indicated, Aged 4 Months, then Exposed to Salt Spray Corrosion Test 30 Days. Specimens 1/16-Inch Thick. A—Water Quenched, C—Oil-Quenched, E—Still Air. See Table Below for Physical Properties of These Specimens.

Specimen	Quenched in	Scleroscope Aged 5 Min.	Scleroscope Aged 5 Days	Tensile Properties Yield Pt., Lbs. Per Sq. In.	Tensile Properties Ult. Str. Lbs. Per Sq. In.	Aged 10 Days Elong. %
A	Water, 60° F.	14.4	26.8	36,560	61,640	18.9
B	Water, Boiling	20.8	26.2	55,640	61,500	19.1
C	Oil, 70° F.	16.4	27.0	35,300	61,400	18.9
D	Air, Fan	18.0	27.0	33,560	59,230	18.0
E	Air, Still	18.0	26.0	33,000	58,900	18.3

A protective treatment known as the "anodic process" for aluminum, duralumin and like alloys, has recently been developed. The process is briefly described in the footnote on this page.*

Corrosion Resistant Alloys. Some progress has been made in the application of corrosion resistant ferrous alloys in aircraft construction. Of these, stainless iron (carbon under 0.12 per cent, chromium 12.0 to 16.0 per cent) has excellent promise, as it can be produced in the form of bar, thin sheet, and seamless tubing, is moderate in cost, is readily fabricated, welds well, and after heat treatment develops physical properties similar to those of alloy steels now used, which it may therefore replace without change in

*The "anodic process" for aluminum, duralumin and like alloys consists of cleaning the parts in carbon tetrachloride to remove grease, and then making the parts the anode in a 3 per cent solution of chromic acid (CrO_3), agitated and maintained at a temperature of 104 degrees Fahr. (40 degrees Cent.), the steel tank being the cathode. This produces a clean gray coating apparently of aluminum hydroxide, of imperceptible thickness, which has a remarkably good resistance to corrosion, and takes stain, enamel or varnish well. Tensile specimens of duralumin sheet, 0.008 inch thick, treated by this process, showed a tensile strength of 50,000 pounds per square inch after 60 hours' exposure to the salt spray test, whereas untreated specimens were badly pitted and had their tensile strength reduced to 10,000 pounds per square inch. An interesting and useful feature of the treatment is that it brings out flaws, segregations or bad welds in duralumin, making them plainly visible.

design. It is one of the few so-called stainless or corrosion resistant alloys which will withstand salt water.

Some of the high nickel and chromium ferrous alloys also have favorable characteristics for certain phases of aircraft work, being tough and ductile, resistant to flame, very resistant to corrosion without heat treatment, easily welded, etc.

Inspection During Fabrication

A competent metallurgist should have active technical supervision over all processes in the shop involving the properties of metals. This includes especially all operations in which metals are heated, such as casting, welding, brazing, soldering, forging, hot forming, and heat treatment. Neither shop men nor shop executives can be expected to possess the specialized knowledge of the characteristics of metals, which will enable them to decide the many and diverse questions of practice which constantly arise in an aircraft factory. Experience has shown that dangerous and costly errors frequently result from their lack of such knowledge. During shop processes, injuries may be done to parts which are difficult or impossible to detect on subsequent inspection, so that the process itself must be inspected. Whenever possible, tests and inspection should be such as to detect the presence of flaws, inferior or incorrect material, failure to respond properly to heat treatment, or inferior properties caused by detrimental treatment. This is one of the most important of the various functions of the metallurgist. He should cooperate closely with the inspection forces in maintaining quality standards. It is not unusual for him to have charge of inspection forces, under the chief engineer.

Study of Failures and Defects

The failure of a certain percentage of parts to meet final requirements, and even the occasional failure of a part in service due to a fault of material, workmanship or design, must be recognized as a possibility, even when the utmost care is exercised. Failures of parts to pass final inspection, are costly and cause delay. Failures of parts during flight are always dangerous, though not always disastrous. Both should be reduced to an absolute minimum and the same failure should never be repeated. This can be insured only by an open and rigorous examination into each case, to

determine its cause, so that precautions may be taken to prevent its recurrence. For the study of metal parts failures, a well equipped metallurgical laboratory is indispensable.

A large proportion of failures in service are traceable to progressive fracture, starting at a small point where stresses have been concentrated, and spreading until rupture occurs. Such fractures are usually due to abrupt changes of section without the presence of adequate fillets, to sharp re-entrant angles, to minute cracks produced in brazing, welding, or heat treatment, to mechanical damage or tool marks, or to the presence of local flaws or irregularities in the metal. A prompt and thorough metallographic examination will ordinarily reveal the cause.

A less frequent cause of failure is defective heat treatment, especially overheating, insufficient soaking, or inadequate tempering.

Corrosion, due to inadequate protection, has been the source of numerous failures in service.

Internal stresses, in severely cold-worked material, are a well known cause of so-called "season cracking" in brass or bronze, and may also cause failure in steel, especially where exposed to corrosion.

Internal stresses produced by cold rolling and excessive vibration or fluttering during flight were assigned as the cause of a series of failures of streamline stay wires. Moderate tempering of the wire to remove internal stresses, resulted in increasing its strength. Fluttering was prevented by restraining the wires at points along their length, whereupon failures ceased.

Embrittlement of duralumin, due to a form of intercrystalline corrosion which was not detectable by surface examination, at one time caused anxiety. This action was not serious when the metal was properly protected, and only reached a dangerous point in parts which had been subjected to severe corrosive action, such as prolonged contact with moisture, or spilling of an anti-freeze mixture, containing the highly corrosive salt, calcium chloride.

New Materials and Processes

The demand for increased performance, safety, reliability and comfort in aircraft, is a constant spur to the adoption of new and improved materials and processes, most of which are in the field

of metallurgy. These should have a thorough test in the laboratory to determine their fitness for aircraft use, followed by a period of observation in service, before adoption on an extensive scale. Unforeseen difficulties not infrequently arise.

Summary

The construction of aircraft is becoming a metal working industry, and one demanding the utmost in materials, processes, workmanship and design. Success from the standpoint of safety, economy, and performance, depends to a large extent upon application of the best metallurgical practice, in a wide variety of metals and processes. Among important points to be observed, are:

1. Purchase of metals under suitable specifications, including chemical analysis and physical properties.
2. Inspection and test of raw material, to insure that specifications are met.
3. Correctly identified stock, stored in orderly manner.
4. Standardization upon a minimum variety of metals and treatments.
5. Restriction of each grade of steel to a standard S. A. E. analysis, or within similar or closer chemical tolerance limits.
6. Accurate and detailed shop specifications for the heat treatment of each grade of steel or other metal.
7. Hardness tests of parts, after quenching, to designate correct tempering temperature, as indicated by heat treatment specifications. Final hardness tests after treatment.
8. Reliable pyrometers, frequently checked.
9. Properly designed and operated furnaces, quenching equipment, etc.
10. Intelligence, care and conscientious attention to instructions on the part of the heat treater.
11. Active technical supervision of all operations influencing the properties of metals, by a competent metallurgist, and immediate investigation of all failures to determine their cause and prevent their recurrence.

An illustration of the results obtainable by the application of these principles is found in the heat treatment records of a large aircraft factory, over a period of four and one half years, which is summarized below. All work was rigorously inspected after heat

treatment by an unbiased inspector. Failure to fall within specified rather narrow Brinell hardness limits, cracks, warping, excessive scale, etc., were cause for rejection.

The value of the individual parts ranged from about $0.25 to $250.00, probably averaging about $25.00. While the output was not large according to production standards, the same principles would apply to an even greater extent, where the output is larger.

Heat Treatment Log—Naval Aircraft Factory

Period	Total Parts Treated	Rejected after Heat Treatment	Per Cent Rejection
1918*	75,431	6,669	8.85
1919	72,287	173	0.24
1920	103,921	44	0.042
1921	249,376	35	0.014
1922	88,312	1	0.0011

*Half Year—July to December inclusive.

The annual savings in labor and material well exceeded the cost of control, so that greatly increased safety and the avoidance of replacement delays were clear gain.

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DISCUSSION

Written Discussion: By Harvey A. Anderson, Bell Telephone Laboratories, Inc., New York City.

This valuable and authoritative paper by Mr. Knerr is particularly opportune at this time. While public interest is focussed on the remarkable successes and lamentable failures of transoceanic flights, there is afforded an unusual opportunity for the metallurgist to impress on the executive the importance of proper choice and inspection of the materials in apparatus and structures.

In a course in surveying, the student is impressed with the fact that the conduct of a survey and the degree of accuracy is governed by economic considerations. A primary triangulation carried out by the Government, requires an accurate closure which warrants the enormous costs. The survey of a piece of woodland by a county surveyor may accomplish its purpose just as effectually at a much lower cost, since the required accuracy is so much less.

Economic considerations should govern choice of materials and their inspection and fabrication. In certain instances, such as a flight across the ocean, major stress-carrying members should be as nearly 100 per cent dependable as is possible by unlimited attention to choice and inspection of materials as well as of the completed structure. It is highly probable from the published reports of the disasters in the Dole flight that some of the loss of life was due to too hasty engineering of certain of the planes. It would appear that these planes should have been constructed under specifications which would require 100 per cent inspection of the parts.

Another notable example of structures which probably should require 100 per cent inspection are the rails used on heavy traffic railroad lines. Serious loss of life has resulted in many instances from rail features of a type commonly known as "internal transverse fissures". These failures grow from nuclei at the middle of the head and spread outward in a manner which precludes the possibility of the trackman detecting the nearness of failure in many cases.

Another illustration of a part where 100 per cent inspection is economically justifiable, is the telephone linesmen's safety belt. The strap and fittings

on which the man's safety depends are of a character where the maximum amount of consideration to choice of materials and their inspection, will constitute an expense which is a justifiable item in any carefully controlled budget.

This question of 100 per cent inspection is capable of being interpreted in a number of ways. It may consist of actual proof-loading to or beyond the expected maximum load to be encountered in service. More commonly, however, it consists in mechanical, chemical, electrical or magnetic measurements on the parts of apparatus in process. The most common check on heat treatment operations is the hardness test and the Rockwell test, which is not mentioned by Mr. Knerr in his summary, has in many instances been found to be the most informative for a given expenditure of time and money. If the Rockwell test can be carried out more rapidly than the Brinell hardness measurement and give comparable information, it is of course possible to test a larger number of pieces or make more measurements on each piece. We have found the Rockwell measurements to be a valuable means for checking the quality of steel and nonferrous metals both in the condition as received and during heat treatment operations.

Rapid polishing and etching methods, including deep etch testing, make possible the examination of the structure of metals in many cases and prove especially valuable for the examination of the character of welded joints. Where defective structures are revealed in the case of welds or of other metal parts, an intelligent interpretation of the results of high power microscopic studies, using methods such as those which have been developed by Mr. F. F. Lucas with whom the writer is associated, will frequently point the way to the correction of defects. The value of such conclusions are of course dependent on the extent to which the metallurgist has supervision, or at least detailed information, regarding the shop processes involving the properties of metals, as is so clearly pointed out by Mr. Knerr in his section on "Inspection During Fabrication."

The importance of the single and repeated bend test, as well as of hardness measurements, as an inspection substitute test for the more expensive tensile and compressive strength measurements is becoming more generally recognized. The noteworthy work of Dr. DeForest on magnetic analysis and that of Dr. Lester on X-ray examination, as well as of others in these fields, gives promise that these methods of inspection will rapidly come into more general use.

One of the most valuable parts of Mr. Knerr's paper consists in the large amount of data which is tabulated for the materials which have been standardized for use in naval aircraft, due, in considerable part, to his efforts. It would be of interest for him to discuss at greater length the reasons underlying the choice of the six steels listed in Table II, other than avoiding confusion of materials in stock. There appears adequate reason for the addition of the chromium-molybdenum steel for tubing because of its superior weldability, and it may be questioned as to whether certain nickel-chromium and silico-manganese and other alloy steels do not have distinctive properties which would justify their use for certain aircraft parts.

It would also be of interest to have further information regarding the characteristics of the chromium-molybdenum steel which gives the noteworthy combination of 60,000 pounds per square inch yield point with 12 per cent elongation in a welded joint without subsequent heat treatment. Presumably, such high joint efficiency could not be expected unless the welding technique is carefully chosen and information on this subject will be welcomed by all who are interested in welding developments. If corrosion resisting characteristics could be combined with high strength and welded joint efficiency, it would appear that the ideal combination metal had been obtained for tubing and similar structures where inspection of such surfaces as the inside of the tubing is practically impossible.

Another of the outstanding merits of this paper is its recognition of the dependable part which light alloys play in aircraft construction. The remarkable performance of the Wright Whirlwind engines embodying cast aluminum alloy parts, together with the conclusion that embrittlement of duralumin is not a cause for anxiety except where the metal has not been properly protected, should be reassuring to many present and prospective users of these alloys.

An interesting application of heat treated high strength aluminum alloys in a part where even the slightest flaw will cause failure, is in the stretched diaphrams for radio broadcasting transmitters. Duralumin sheet less than 0.002 inch thick has been functioning satisfactorily for this purpose when stretched to a stress approximating its tensile yield point in apparatus which has been in service over a period as great as several years. This application of high strength aluminum alloys furnishes one of many examples where aircraft developments have proven of great value in other engineering fields.

Written Discussion: By T. W. Downes, metallurgist, Naval Aircraft Factory, Philadelphia.

The subject of aircraft metallurgy is one upon which much could be written, and for this reason the task of covering most of the phases thereof thoroughly, yet concisely, is most difficult. This, however, the author has accomplished most creditably, having been forced, no doubt, for the sake of brevity, to condense and abbreviate to the point of omitting much pertinent information and data.

Under the heading of new materials the writer wishes to call attention to the "Alclad" products of the Aluminum Company of America, which are the sheet form of the strong, heat treated, wrought aluminum alloys upon the surfaces of which has been superimposed a thin layer of aluminum of relatively high purity. These materials, having practically the same mechanical properties as the base metal, but greatly superior resistance to corrosion, even when the aluminum coating is ruptured, must surely soon find an important place in aircraft construction.

Although not new, the 2 per cent manganese alloy of aluminum is considered worthy of mention. The sheet form of this material is appreciably stronger than pure aluminum subjected to the same degree of cold working and compares very favorably with the latter metal in corrosion resistance. In

view of these characteristics it is not apparent why this material has not found more extensive use in place of aluminum in the construction of aircraft.

Chromium-molybdenum steel is finding increasing favor in aircraft construction for various reasons chief among which, in addition to those pointed out by Mr. Knerr, are the wide latitude of the satisfactory quenching range and the retarded grain growth upon unnecessarily long exposure to the quenching temperature.

Written Discussion: By Lieutenant Commander William Nelson, U. S. Navy.

The paper presented by Mr. Knerr is, undoubtedly, a very comprehensive write-up on the general subject of metallurgy in aircraft construction. It can be seen from the paper that metallurgy enters into the many phases of aircraft building, so that it is undoubtedly one of the most important branches of the aircraft industry.

One of the most important points connected with aircraft at the present time is the changing over from wood construction to metal construction. The military services throughout the world are making changes which are advantageous to aircraft operation, and which entail primarily the change over from wood to metal. In the commercial fields, the shift from wood to metal is being made more gradually, but there does not seem to be any great doubt but what metal aircraft is that of the future. This tends to make the demand on metallurgy much greater than it is at present.

One of the most important features connected with aircraft construction, which is not met in the construction of other units, is the demand that the designer obtain the ultimate in each piece that is built into the craft. In the production of units such as automobiles, etc., rather large factors of safety can be used; in the building of aircraft, it is necessary to obtain the maximum strength at the minimum expenditure of weight. This causes a reduction of the factor of safety to a point where it is absolutely essential that the materials to be used in aircraft are constant and that everything is known regarding their behavior when finally completed.

The general subject of metallurgy in the aircraft industry has been ably covered by Mr. Knerr, and it is believed that the American Society for Steel Treating should look forward to additional papers on the application of metallurgical science to the aircraft industry, with a view to giving a great many details, which are always a help to those who deal in this type of work.

Written Discussion: By G. W. Lewis, director of aeronautical research, National Advisory Committee for Aeronautics.

I consider the paper most interesting and valuable, as it presents to metallurgical engineers the scope of the application of metal structures in the aircraft industry.

The composition of duralumin appears to be in error by the omission of silicon. I understand that silicon plays an important part in the hardening of duralumin and usually is present to the amount of about 0.5 per cent.

The statement, that "square tube is stiffer than round tube of equal weight and equal diameter (across flats)" may be amplified. Some recent

experiments on the failure of airship girders indicate that the compression failure of many sections takes place in reality by failure in torsion. If the column or tube is restrained so as to resist a tendency to failure in torsion, the failure then takes place by lateral bending at a higher load. If restrained from torsion failure, the square tube would be stiffer and better in bending than the round tube. If torsion is not restrained, the circular tube gives better results than the square tube.

Oral Discussion

J. L. McCLOUD: I have noted Mr. Knerr's discussion of the protection of parts, particularly those parts that are welded in fabrication. This brings to mind the necessity that we have found of adequately drying the parts after plating, as for instance, parts that are fabricated from sheets or tubes, with sheets or plates welded to them. There are often cavities that are very small and apparently insignificant that, during the process of plating, become filled with the plating solution, and unless this solution is dried out, corrosion, or rusting of the parts, may occur afterwards, even though they may be well plated. We have found it quite necessary to dry these thoroughly by treating them in oil at such a temperature that it will drive out all moisture.

R. F. COHN: Mr. Knerr makes reference to plating with zinc instead of cadmium. I am much interested in the relative merits of zinc as compared to cadmium for such exposed parts of an airplane. I would like to ask the author whether the zinc was plated from a cyanide bath or from a sulphate bath and, if possible, a little more information as to the two types of coatings in question.

H. C. KNERR: Both sulphate and cyanide baths were used at the Naval Aircraft factory, and the zinc plating done there withstood the Navy test of 100 hours salt spray very well. We had great difficulty in getting zinc plating from commercial concerns to stand that test, but finally found a few who could do it.

Cadmium plating is rather a new development, but the results have been very satisfactory and I think it will come into rather general use.

With reference to Mr. Anderson's remarks concerning the Rockwell hardness test, I purposely omitted mentioning any particular type of test because each method, the Rockwell, the Brinell and the Shore scleroscope, has its proper field in aircraft work. All have been used very effectively.

MR. LOUCKS: (Line Officer, Canadian Aircraft) I notice you showed some pictures of fractures in stream line wire. Might I ask whether those fractures were taken from the flying wires or from the landing wires, as in the periods of vibration a flying wire, if it vibrates in the air, usually vibrates very quickly, whereas a landing wire, which, of course, in the air is loose, vibrates very slowly. I have had considerable experience with this breakage and would like a little more information as to what you found, both where the break occurred and whether it was more apparent in the flying or in the landing wires.

H. C. KNERR: The breaks were, in the majority of cases, in the landing wires, that is, in wires not stressed during flight. These, being compara-

tively slack, showed the most vibration. The location of the fracture was usually a few inches from a fixed end of the wire.

A. D. CAMP: I might add something to what Mr. Knerr has said in regard to the protection of aluminum against corrosion, especially after welding operations. We have found it extremely desirable, in fact, imperative, to remove all traces of welding flux, and if this is not done, the flux being hydroscopic, will absorb moisture from the atmosphere and start very detrimental corrosion. We have found that the best measure for removing welding flux is dipping and washing in hot two per cent nitric acid or sulphuric acid solutions followed by water washing. This has proved quite effective in removing flux from hidden corners and angles that are difficult to wash out with water or steam. Fused flux effervesces when in contact with acid, and therefore disintegrates very rapidly.

I would say also that the application of welding wire composed of five per cent silicon and ninety-five per cent aluminum in the welding of strong aluminum alloys has been of great help in eliminating cracking. The deposition of the five per cent silicon welding wire appears to relieve strains in the structure caused by the thermal effects of the welding torch and therefore makes very strong joints.

Author's Closure

In closing, the author wishes to thank those who have so kindly contributed discussion, comments and criticism, and to express his grateful acknowledgement to those who have permitted the use of certain data and illustrations.

The subject of aircraft metallurgy is so broad and complex that to consider its various phases in any detail, within the scope of a technical paper, would obviously be impossible. Limitations of space have necessitated pruning the original manuscript almost to skeleton form and omitting numerous illustrations. Many of the points touched upon are discussed more fully in the references. The welding of aircraft members has been ably discussed by J. B. Johnson,[1] in a contemporary publication.

An earnest attempt has been made to chart the subject as a whole and to present in condensed form the more fundamental facts and principles as they appear today. If the effort proves of some service to the great new industry which is taking so important a place in our civilization, the author will be deeply gratified.

[1] *Journal*, American Welding Society, September, 1927.

THE CORROSION OF METALS

By Dr. William M. Guertler

Abstract

The author discusses the problem of the corrosion of metals as it confronts the metallurgist. He points out the enormous economic waste due to corrosion and the many factors which play a part in the corrosion of metals and their protection against corrosion. From his study of the subject, he derives many valuable and highly practical conclusions as to what may and may not be expected as to the corrosion resisting qualities of different metals and alloys.

He states that the basis of all commercial acid resisting alloys necessarily must be the group of elements, iron, nickel and copper. The various elements that might be added to improve mechanical, electrical and other properties should be taken up by them in solid solution. The one-phase homogeneous structure characterizes all of the highly resistant alloys no matter how complicated the composition; that is, every crystal contains all the metals present in the same amount and in solid solution.

The author explains that no one permanently durable alloy can ever be developed which will be resistant to all acids.

IN DISCUSSING the problem of corrosion, I wish first to direct attention to the fact that the problem of corrosion and the problem of acid resistivity, or the chemical behavior of metals and alloys, are two problems, which are inseparably related. We know for example that many kinds of water which might start corrosion, will, in the presence of air, take up oxygen and carbonic acid and so become oxidizing acids. Others, such as sea water, may contain salt, and on evaporating down become quite concentrated oxidizing acid-salt solutions. Thus it is that the problem of ordinary corrosion becomes closely associated with the problem of acid resistivity.

As an example of the importance and magnitude of the destructive effect of corrosion, it may be stated that from the year 1890 to

This paper is the first Edward De Mille Campbell Memorial Lecture presented before the eighth annual convention of the Society, held in Chicago, September 20 to 24, 1926. The author, Dr. William Minot Guertler, member of the Society, is associated with the Metall-Institut der Technischen Hochschule, Berlin, Germany.

1923 a total of thirty-three years there have been 1,766,000,000 tons of iron or steel recovered from its ores. Of this amount 718,000,000 tons have been lost by corrosion, acid attack and so on. That is really an enormously great loss, and it is a very important thing to know. On the other hand, we know that the present requirements of the chemical engineer and others call for alloys which resist special chemical reagents and, consequently, some attention will be directed to the general theory of this problem.

Fundamental Conceptions

Pure Metals

Coming now to our problem, we may first raise the question,—What is it that makes a metal corrode or what makes it resist the attack of a strong salt solution or of an acid? In answering this query, we shall take up the pure metals first and then their alloys later; but to understand the problem, fundamentally, we must consider certain of the general laws of chemistry. Those laws which particularly concern us are the laws of chemical statics and the laws of chemical kinetics.

Statics

Chemical: It is probably well known to you that the metals have a certain affinity for the nonmetallic elements, and that this affinity can be studied in different ways. The first method is by purely chemical means. We may, for example, mix aluminum powder with ferric oxide, heat the mixture to an elevated temperature and note that the aluminum takes the oxygen from the iron oxide to form alumina, and that the iron is set free. This simple test establishes the relative affinity of oxygen for aluminum and iron in a purely chemical way. If we were to perform such experiments with various mixtures of metals and metallic oxides, we could then list the metals according to their affinity for oxygen so that any metal would be able to take oxygen from the metals standing below it, but that oxygen would be taken from it by all the metals standing above it. We could establish, in the same manner, the relative affinities of the metals for sulphur, chlorine and so on. Such tabulations would show different arrangements of the metals for the nonmetallic elements tested but, even so, it is only the relative and not the absolute affinity which is brought out. If we would evaluate

the absolute affinity of a metal for a nonmetal, we may utilize thermochemical measurements.

Thermochemistry: We know from thermochemistry that if two elements combine and form a chemical compound, there is a certain amount of heat evolved. While this amount of heat does not always quantitatively measure the chemical affinity of the elements, however in all the cases which are considered here, it gives an absolute comparability. Therefore, by measuring the heat of formation of any one of the chemical compounds, we can obtain the affinity of the two elements. Some of these measurements are plotted in Fig. 1 for the heat of combination of different oxides. As abscissae, we have the number of atoms of oxygen taken up by one atom of the metal and as ordinates, the number of calories per gram-atom evolved by one molecule of oxide formed. On the first vertical line are plotted the oxides of the monovalent metals and on the next those of the bivalent metals which take one atom of oxygen per one atom of metal. On the third line we have one and one-half atoms of oxygen per atom of metal, etc. Now, if we connect these different points of the plot with the origin, the slopes of such lines will give the amounts of heat evolved for equal amounts of oxygen with which the metal combines. The slopes of these lines, therefore, will give a measure of the chemical affinities of these metals for oxygen.

For example, aluminum will take oxygen from the oxides of all the metals to its right side and aluminum oxide itself will be decomposed by all the metals on the left. You will see also that only gold (nitrogen and chlorine, which are not of interest here) is on the negative side below zero and has a negative affinity for oxygen. That means that gold oxide would be unstable; it would be liable to break down into metal and free oxygen. If we were to make the same tests, not at ordinary temperatures, but at a higher temperature, we would find all these values to be a little lower, and that the lines would all rotate to the right at the same time, while their relative positions would change a little, and at still higher temperatures they would all approach the zero line. The first metals to have zero heats of formation would be perhaps, silver, palladium and platinum. The moment any metal crosses the zero line and passes to the negative side, that metal gains absolute stability, and above this temperature, its oxide decomposes. Above the decomposition temperature, the metals are absolutely stable in contact with oxygen. From this we see (Fig. 1) that all of the common metals are un-

stable in the presence of oxygen, and that they need very high temperatures in most cases, to make them stable.

If, instead of oxygen, we select another element such as sulphur, (see Fig. 2,) we find that the arrangement of the metals is a little different. In this case lithium is the metal which has the strongest affinity, then calcium, and so on.

If we take chlorine, then we find that caesium has the strongest affinity, then potassium, barium, sodium, calcium and so on. Here

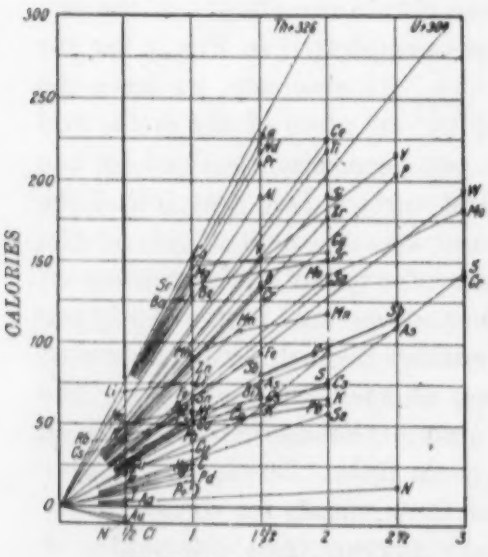

Fig. 1—Heat of Formation of the Oxides.

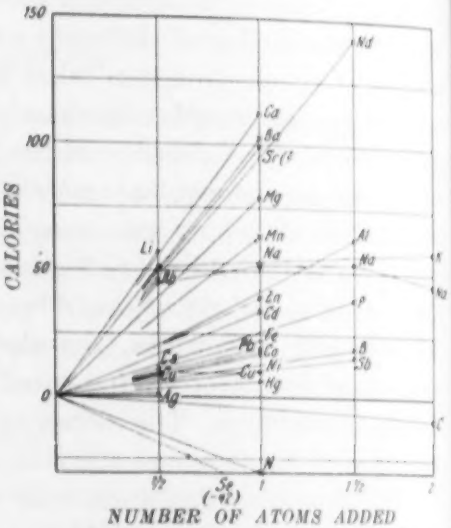

Fig. 2—Heat of Formation of the Sulphides.

we see that gold is now on the positive side, which means that gold has a positive affinity for chlorine. As is well known, gold dissolves slowly in a chlorine solution. (Fig. 3.)

And now we will consider the last case, or the affinities of the metals for fluorine. Here the strongest affinity is with calcium. Therefore calcium fluoride would not be decomposed by any other metal. (Fig. 4.)

All this goes to show that we ought not talk about the "nobility" of a metal or about the greater affinity of one metal as compared to other metals in general, because the affinity of a metal is always relative to the kind of nonmetallic elements with which it combines.

Electrochemistry: Finally we have another method of studying chemical affinity; that is, by the methods of electrochemistry. The basis of this is the electrolytic solution pressure of the different

Table I
Equilibrium Potentials

Electrode Measured	E. M. F.	E. M. F. 1 n Ionic Conc.	Authority
Li/Li ions, 1 mol in Ethylamine	.....	−3.018	Lewis and Keyes (1913)
Rb/1 n Rb salt	−2.919	.....	Lewis and Argo (1915)
K/K ions, 1 mol in Ethylamine	.....	−2.922	Lewis and Keyes (1912)
Na/Na ions, 1 mol in Ethylamine	.....	−2.712	Lewis and Keyes (1910)
Mg/0.5 n $MgSO_4$	−1.588	−1.56	Kistiakovsky (1908)
Al/AlBr in Ethyl-bromide, 40.95%	−1.374	.....	Patton (1904)
Al/$Al_2(SO_4)_3$	−1.326	.....	Neumann (1894)
Mn/0.5 mol $MnSO_4$	−1.089	.....	Neumann (1894)
Zn/0.5 mol $ZnSO_4$	−0.800	−0.77	Kistiakovsky (1908)
Cd/0.5 mol $CdSO_4$	−0.426	−0.40	Lebendzinsky (1904)
Tl/sat. sol. TlCl, ionic conc. 0.0143n	−0.440	−0.331	Lewis and Ende (1910)
Fe, powder/0.5 mol $FeSO_4$	−0.47	−0.44	Foerster (1909)
Fe, vac. fused/0.5 mol $FeSO_4$	−0.424	.....	Richards and Behr (1907)
Ni, powder/0.5 mol $NiSO_4$	−0.33	−0.30	Schweitzer (1909)
Ni, sheet/0.5 mol $NiSO_4$	−0.31	.....	Schweitzer (1909)
Co, powder/0.5 mol $CoSO_4$	−0.31	−0.28	Schildbach (1910)
Co, compact/0.5 mol $CoSO_4$	−0.29	.....	Schildbach (1910)
In/1 mol $InCl_3$	−0.33	.....	A. Thiel
Sn/1 mol $SnSO_4$	−0.187	.....	Foerster and Gamasoti
Pb/1 mol $Pb(NO)_2$	−0.153	−0.127	Lewis and Brighton
H/1 mol H_2SO_4	0.00	0.00	
Ta/0.006 mol TaF_5	+1.65	.....	Hevesy and Slade (1912)
Bi/1 mol $BiCl_3$	+0.141	.....	Neumann (1894)
Sb/1 mol 0.33 $SbCl_3$	+0.106	.....	Neumann (1894)
U/aq. UCl_4	+0.23	.....	Fisher (1914)
As/1 mol 0.33 $AsCl_3$	+0.276	.....	Neumann (1894)
Cu/0.5 mol $CuSO_4$	+0.307	.....	Abbeg and Lebendzinsky (1904)
Cu/0.5 mol $CuSO_4$	.....	+0.3469	Lewis and Lacey (1914)
W/aq. sol. WCl_6	+0.609	.....	Fischer (1914)
Hg/0.05 n $Hg_2(NO_3)_2$	+0.730	.....	Ley and Heimbucher
Ag/0.5 mol $AgNO_3$	+0.775	+0.80	Brislee (1909)
Pd/0.5 mol $PdCl_2$	+0.792	.....	Neumann (1894)
Pt/0.25 mol $PtCl_6H_2$	+0.866	.....	Neumann (1894)
Au/0.01 mol $AuCl_3$, polished	+1.173	.....	Fawsitt (1906)
Au/0.01 mol $AuCl_3$, annealed	+1.180	.....	Fawsitt (1906)
Au/0.01 mol $AuCl_3$, hammered	+1.148	.....	Fawsitt (1906)

metals, which by some mathematical law, is related to the chemical affinity. In Table I is given the solution pressures from which we get the force by which a metal is driven into solution to combine with a nonmetallic element, which is in this case, sulphuric acid. You will find again about the same seriation of metals as before: lithium, potassium, sodium, magnesium, aluminum, zinc, cadmium, iron, nickel, cobalt, tin, lead, bismuth, antimony, copper, tungsten, mercury, silver, gold and so on. It is similar to that for heats of combination, but not exactly the same. Between lead and tantalum we find hydrogen; from the standpoint of a chemist it is metal, though in the gaseous state, whereas from the standpoint of the engineer, of course, it is not a metal.

Now, hydrogen comes along toward the middle, and that means that sulphuric acid will be decomposed by all the metals standing above hydrogen, and that only the metals below hydrogen cannot break down sulphuric acid. Therefore, all the metals above hydrogen

would be unstable only in case the sulphuric acid contained free oxygen in solution.

In Fig. 5 we find the different electrolytic potential series of the common metals for different solutions. The first row was taken from my book, the next from Foerster, the next one from Nernst, while row IV was measured in sulphuric acid, V in water, VI in

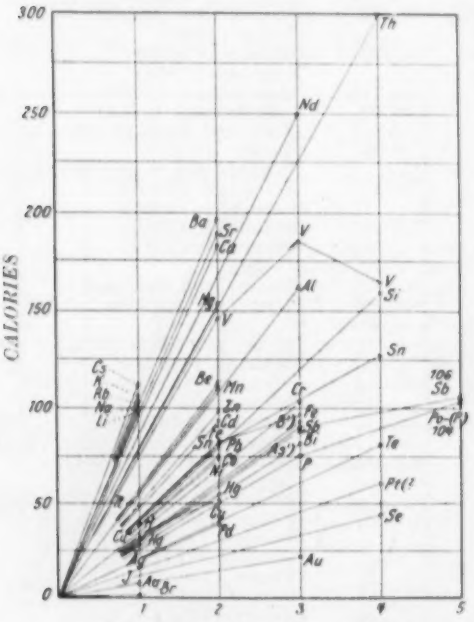

Fig. 3—Heat of Formation of the Chlorides.

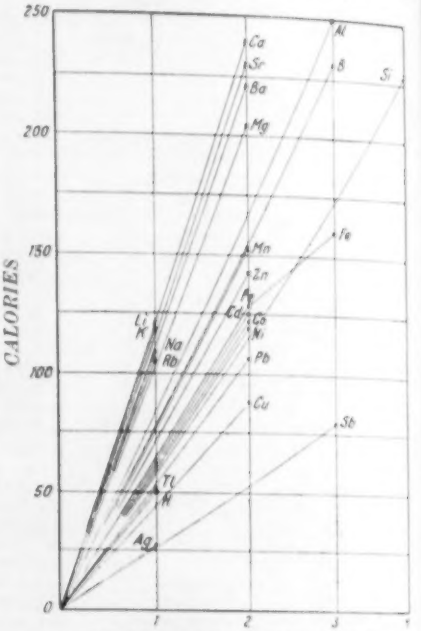

Fig. 4—Heat of Formation of the Fluorides.

dilute nitric acid, VII in concentrated nitric acid, and VIII in potassium cyanide. This is only to show that the relative positions of the metals change considerably. For example, if we follow lead, we find it first in a very low position, later it goes up and from VII to VIII it falls off again. Most of the changes in position come between rows VII and VIII due, you will understand, to the formation of complex salts with potassium cyanide.

Now, keeping in mind what we have learned before, that the chemical behavior of the metals is absolutely different for different kinds of reagents, we will see that here too one metal is better in one case, and another metal in another case. That is a very important statement which will be discussed later.

The facts advanced in this section on chemical statics, whether they relate to the simple chemical behavior of the metals, or to the quantitative data of thermochemistry and electrochemistry, show

that in every case all our metals and alloys are unstable in the presence of oxygen and water. That of course is a very sad state of affairs, but fortunately it is not the complete statement. We have, for example, the case of the famous iron pillar at Delhi, which has withstood the buffetings of the weather for centuries. This pillar is not very pure iron, because it contains slag and many other impurities. On the other hand it is not a modern special alloyed

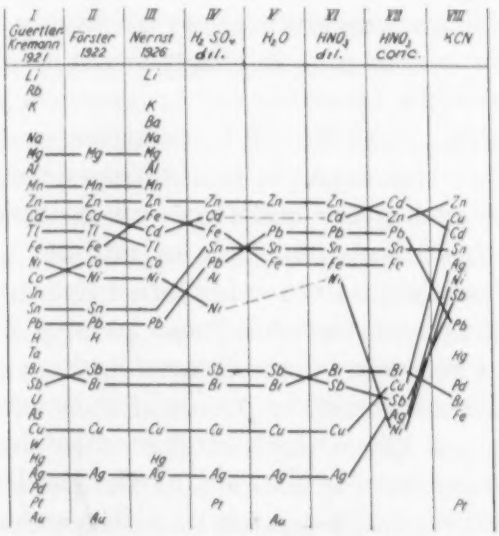

Fig. 5—The Electromotive Series.
Rows I to III are Decomposition Voltages at Normal Concentrations. Rows IV to VIII are from Winkelmann's Handbook of Physics, 1905.

steel and yet it remains today, uncorroded. This means that although this iron column has a very great affinity for the oxygen of its environment, nevertheless it could stand a very long time, in a well preserved condition. Therefore, there must be something else besides the laws of chemical statics and affinity, which controls this behavior, and so we shall turn to chemical kinetics.

Kinetics

You all know that if we mix hydrogen and oxygen, two elements which have a very great affinity for each other, these two kinds of atoms are capable of remaining in close contact with each other without combining. There is certainly an intimate molecular mixture, but if it is not heated, no chemical reaction will ensue for an indefinite period. From this we see that there often is a certain sluggishness or inhibition which materially effects the course

of a chemical reaction. And that is what really saves our metals and alloys, as indeed it protects all organic nature, because all organic nature is not only unstable in the presence of oxygen, but often is unstable internally.

Temperature. We have now to consider some of the different factors which alter or retard these reactions. The first one is temperature. An increase of temperature always means an increase of reaction. In many machines, like steam turbines, motors and so on, we cannot avoid high temperatures, so we simply have to face the danger from this source and it is important to recognize the accelerating effect of this factor.

Catalysis. The next factor is catalysis or the catalytic influence. We know, for example that nitrogen and oxygen have a great affinity for each other and that even so they exist mixed in the atmosphere for many thousands or millions of years without combining. In fact they do not enter into reaction even at elevated temperature. It has been discovered that under these circumstances, we can promote a reaction; that nitrogen and oxygen can be made to combine to form nitric acid by means of some catalytic substance. We generally do not know which kind of substance will have this effect and we simply have to find out by the empirical method. In our case we do not want such a catalytic action and it is best to avoid all substances which might provoke such action.

Sometimes in chemical solutions which must be used, the presence of catalysts cannot be avoided, but in metals they can be avoided by eliminating all impurities, outside of the main crystalline constituents which form the alloy.

Electrolytic Effects. Next we come to the effect of the formation of electrolytic cells. For example, if to a solution of zinc sulphate, a sheet of copper and a sheet of zinc be added, an electrolytic cell is formed. If the two sheets are connected an electric current will flow, and the zinc will dissolve rapidly while hydrogen will be evolved at the copper sheet. If the electrical contact is broken, the zinc will not dissolve, or at least not so rapidly. By making these two metals touch each other beneath the surface, the same effect will be produced as that of short circuiting; the electric current, by simply flowing through the water and the two metals, will make the zinc dissolve rapidly. As a practical example of this effect we may take a sluice gate that is made of steel, with special parts made of bronze. Here we will see in a very short time that those parts

of the steel which are next to the bronze parts will be badly corroded. In the same way the corrosion of aluminum articles is greatly hastened by the presence of white-metal solder. Therefore one should avoid connecting two different metals, especially when they have greatly different electrolytic solution pressures or potentials.

Protective Coatings. The fourth factor, which is very important, is that which is introduced by the formation of a protecting layer which forms automatically on the surface of the metal. We know that all metals are crystalline, and that every crystal is built up by the atoms arranging themselves on a space lattice. At times, this space lattice is very regular. However, most of the metals are cubic, and therefore the atoms are arranged in chessboard fashion in all three dimensions. For simplicity's sake we may assume the arrangement to be simple cubic, so that each atom will have six arms to take hold of its neighbors; one left, one right, one upward, one downward, one forward, one backward. Now somewhere the crystal of course must have an end, which will be at a surface. Let us assume that this surface is parallel to the face of the cube. On such a surface every atom has one empty arm extending out into space, while the other five are attached to the neighbors. One arm always must be free because the space lattice stops there. This condition characterizes the whole surface of the crystal with all the unattached arms seeking contact with other similar arms because they represent forces of chemical affinity. We will remember that in the crystalline or metallic state, modern science does not recognize molecules any more, but only atoms arranged on space lattices. Hence there is no difference between chemical affinity and cohesion of the structure of the space lattice.

We may now inquire into the consequences of the presence of these unbalanced forces on the surface of a metal crystal, particularly the effect of these arms (forces) on other atoms which may come within the sphere of atomic influence. In the case of iron or steel, if the arms at the surface get hold of new iron atoms, of course they will take hold of them and continue to build up that space lattice. For example, let some chemical reagent like oxygen come into contact with the surface, each atom having two arms of chemical affinity, assuming that the oxygen is in the gaseous state. We know if chemical reaction starts, that one arm of this oxygen will take hold of the empty arm of an iron atom or chromium atom,

or of whatever is present on the surface of the crystal. The other arm of the oxygen atom may extend outward into space or it may take hold of a neighboring atom of metal. At any event, the whole surface of this metal crystal will be covered with a layer of oxygen which will be mon-atomic at first. Therefore, the surface of the metal at this stage will no longer be a metallic surface, but will be an oxygen surface, and we have strong reason to believe that this accounts for many well-known facts. It accounts for the phenomena of the so-called passivity of metals; it accounts for over-voltage and for the difficulty of getting the last traces of gases to leave the surface of a solid body even in a vacuum and at high temperatures. Of course this amount of gas is not large; only sufficient to cover the metal by a layer only one atom thick.

This state of a thin film has nothing to do with ordinary chemistry; it is neither gaseous nor liquid because the atoms composing the film cannot move over the surface and they cannot go away; they are bound securely in place. And on the other hand the state is not solid or crystalline in the usual sense, because, in the normal crystalline state, oxygen and iron or chromium would form quite a different and definite space lattice, which is the space lattice of the metal oxide. On account of the peculiar physical structure these thin layers have a special chemistry. We have on one side oxygen, and on the other side metal with a strong tendency between the two to combine in the usual way. Now, what can happen? What really happens if the temperature is high enough is that by some process, this thin layer on the surface moves into the metal lattice and that can only be done by a diffusion process. This indicates the point at which diffusion enters and becomes a factor of fundamental importance in corrosion and acid resistivity. The less diffusion we have, the better will be the resistance. If this film of oxygen atoms diffuses in, new atoms of the metal in the surface will be exposed which are ready to combine again with oxygen. In this way the normal well-known oxide will be formed with its own space lattice. We do not know in all cases what space lattice it is, but in the case of chromium it certainly is one with two chromium atoms and three oxygen atoms alternating with each other because the chemist tells us the compound has the formula of two chromium atoms and three oxygen atoms.

Now, then, this space lattice again has empty arms of oxygen and chromium atoms on the outer side, and the same on the inner

side. There it may either unite with the empty arms on the surface of the metal, and cling to them, or it may not. In some cases it will adhere tightly, but even so there will be the danger of rupture, if the temperature be changed, because these two space lattices will have different coefficients of expansion and contraction with the result that the oxide will likely scale off. If this occurs, the action will begin anew. As long as this covering is there, if it is continuous or without pores, it will protect the underlying metal for a long time. Further reaction can only go on by the oxygen atoms diffusing in and the metal atoms diffusing out. It certainly does not proceed by one oxygen atom passing directly through the space lattice of the oxide and then entering the metal. Rather the first oxygen atom takes hold of the next metal atom and pushes the next oxygen atom along and that in turn unites with the second metal atom and pushes the second oxygen atom along. So the oxygen all moves in one direction and the metal all in the other just like boys and girls in the "Chaine Anglaise", the old quadrille dance, which you may recall.

Turning now to the pure metals, we note, for example, that magnesium has this very high affinity for oxygen and that it will nevertheless stand up against water very well. That is because in the first instant it can decompose the water molecules and form magnesium oxide, which is a very resistant compound. It will cover the metal as a continuous film which clings to the metal. It is chemically and mechanically very resistant. It has a very high melting point and is hard and insoluble in water and so on. In the same way, aluminum in water will cover itself with aluminum oxide, which is a compound of the same kind.

In nitric acid, magnesium will be transformed at the surface into magnesium nitrate. Inasmuch as this compound dissolves in water, this will be removed as rapidly as it forms, and no covering will be formed. Therefore the magnesium will dissolve rapidly. On the other hand aluminum resists nitric acid because under these circumstances, it is the oxide which forms, and this oxide is not soluble in nitric acid. Therefore the aluminum will be absolutely protected by this thin film of oxide. Use is made of this behavior in pickling brass castings. The castings are put in a big aluminum basket and the whole dipped into the nitric acid pickle with the evolution of heavy fumes of nitrous acid. The brass is instantly pickled, but the aluminum is not touched at all.

In the same way, magnesium will not be dissolved in hydrofluoric acid because the fluoride is not soluble and silver will not be dissolved in hydrochloric acid because the chloride is not soluble. Lead in a solution of sulphuric acid will cover itself with lead sulphate, but will not be dissolved. Steel in sulphuric acid, if the acid does not contain more than 2 per cent of water, will not be dissolved, because in that case it will form ferrous sulphate, which is not soluble in such a strong acid. This brief account indicates about all the success which can be expected with the use of pure metals.

For certain reasons, which I cannot explain in this limited space, we have at the present time, and we always have had and will for a long time have not more than eight common metals to form the chief constituents of all our alloys. If we do not consider the precious metals, like gold and platinum, which we avoid because they are too expensive and also molybdenum, titanium and tungsten, which are fairly precious metals, then we will be limited to the following eight metals:

1. Two light metals; magnesium and aluminum.
2. Three high melting, heavy metals; iron, nickel and copper.
3. Three low melting, heavy metals; zinc, lead and tin.

So far we have indicated only little success in acid resistivity. From the foregoing it is clear that we have lead for sulphuric acid, and aluminum for nitric acid, and so on. But we have not much more than that. Therefore, we must consider the problem of the alloys, and by alloying, to develop new chemical properties.

Alloys

We probably all know that three different things can happen when we start from one metal and add different quantities of other elements. For example if we add bismuth to copper the microscope will show copper and bismuth present as two different kinds of crystals. We will see the red crystals of copper and the white crystals of bismuth. In this case the chemical behavior is a simple problem. We cannot expect any special properties. If one of the components is dissolved in a chemical reagent, then all the alloys of this type must be dissolved, and we would not expect anything new.

Another example is given by the aluminum-tin alloys. These alloys will also show only aluminum crystals and tin crystals. From

the fact that aluminum is dissolved in a caustic solution, we know that all the alloys of aluminum-tin will be destroyed by the same solution. Tin will be dissolved in strong nitric acid, which aluminum will withstand. Therefore, all the aluminum-tin alloys will be destroyed by nitric acid and we cannot expect that we will ever find any special new properties.

Secondly, we know that in other cases the added element will form a solid solution. For example, if we start from copper again, and add ten per cent, twenty per cent, thirty per cent or any amount of nickel, we will never see individual copper crystals and nickel crystals under the microscope because any addition of nickel will enter the copper crystals themselves, and each crystal will contain the same amount of nickel which was added to the alloy. The copper crystals will become paler and paler, the more nickel they contain, but we will never see isolated crystals of nickel and copper. That illustrates the formation of the so-called solid solution, or we should really say the "crystalline solution," because it is a solution with an added element in the crystals of the first.

The third thing that may happen is this: if we again start from copper, and add antimony, then the antimony will not dissolve in the copper crystals; at least, not to a great extent and neither will there be crystals of free antimony. What we will find will be crystals of a copper antimonide with a new color which is rather more pink or violet. The antimonide is a new chemical body and has quite different properties, in the same way that common salt is different from chlorine and sodium, from which it is formed.

Statics

Turning now to the chemistry of the different types of alloys, we shall again consider the statics first, and then the chemical affinities of the alloys for other nonmetallic elements.

Intermediate Compounds: First we shall consider what we may expect for the properties of such different alloys and it will be well here, as in the case of the pure metals, to consider their chemical, thermochemical and electrochemical behavior.

Chemical Behavior: In a purely chemical investigation we would find, for example, if we treated some alloys which combine with sulphur or chlorine, that the free metal would be first to combine and then the intermetallic compounds. The latter have a lower

affinity, if we study really affinity itself, from the standpoint of chemical statics.

Thermochemical Behavior: With the aid of thermochemistry, it is observed that the formation of such compounds always results in the development of heat—the heat of combination. For example, when two atoms of aluminum and one of copper combine to form a compound, twenty-three calories are given off. What does that mean in the problem of the combination of such compounds with other elements? As we know, both aluminum and copper unite readily with oxygen. If this compound were to oxidize, the two atoms of aluminum liberate four hundred calories and the one atom of copper would liberate forty;—a total of four hundred and forty. We must subtract from this, the twenty-three calories, because it is necessary to break down the compound or to divorce the aluminum from the copper and then to combine both with oxygen. The quantitative evaluation of the affinity instead of being 440 calories is only 417. The affinity to oxygen of the compound is a little less than would follow from the rule of mixtures, but is not far off.

In published data which shows the heat of combination of several intermetallic compounds, the value of 199 for the compound Ca Zn_{10} is given. Here the heat of combination is great. It might be hoped that in some cases it might be greater than the heat of oxidation, but unfortunately, we have such high numbers as 56 for $CaZn_7$ and 61 for Ca_6Na, only in case one metal is a highly active one. In one case it is sodium, and in the other it is calcium, both of which stand out as chemically active metals, and therefore combine energetically with other metals just as they do with oxygen, as is given in Fig. 1.

Fig. 6 will help us to get a general idea of the heats of reaction of intermetallic compounds. Metal A has a heat of combination with oxygen corresponding to point "a," and the metal B one corresponding to point "b." We would expect that the alloys would follow the rule of mixtures, which means that the heat of combination would follow the line a-b. If there is a compound formed having the composition A_m-B_n, and the heat of combination of this compound is ws, then the heat of oxidation of that compound would be uw minus sw equals su, and the heats of the alloys would be on the line "a-s-b." It would be fortunate if in some cases, this heat of combination, ws, might be so big that the

point s would come down to the negative side, which would give an absolutely stable compound, but as I said before, we have no hope that that will ever be realized.

Electrochemical Behavior. The electrochemistry of alloys containing compounds point to the same fact. In Fig. 7 for example the alloys of iron and zinc, we have compounds at C and D and probably at E and F. If we consider the affinity of the different

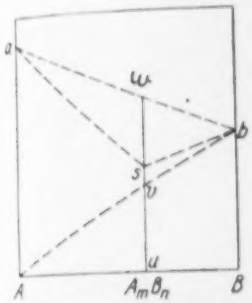

Fig. 6—Diagram Illustrating the Affinity of Two Metals Which Form a Compound.

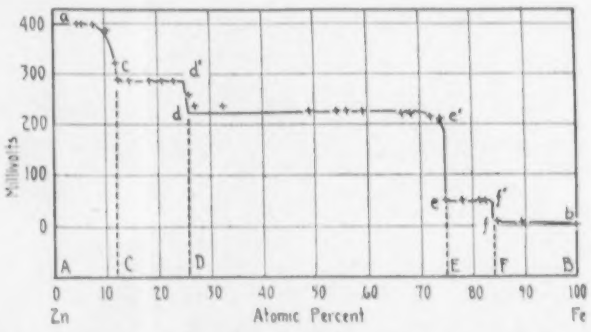

Fig. 7—Curve Showing the E. M. F. of Iron-Zinc Alloys.

kinds of crystals expressed as the electrolytic solution pressure, then the affinity of iron (B) is "b" and that of zinc (A) is "a," while from the rule of mixtures the intermediate alloys would be on the line "a-b." Actually all the points c, d, e, f, belonging to the pure compounds are really below that line, and therefore these compounds are again found to be more stable than we would expect from the rule of mixtures.

On the other hand, where we have mixtures of the two compounds, as for example between the two compounds D and E, the alloy as a whole will always have the electrolytic solution pressure of that compound which has the higher pressure. This accounts for horizontal lines in some of these mixtures like "d-é" which come above the line of the rule of mixtures. The part "x-é" comes very much above the line "a-b". This shows that the presence of two different kinds of crystals is detrimental from the standpoint of statics alone and this factor often overcomes the benefit of the higher stability of the compounds themselves. We may further conclude that we should avoid such alloys, and use only those which have only one kind of crystal, or those in which the metals present form solid solutions.

Aside from the feature just mentioned, the chemical compounds have another drawback. They are all, or practically all, exceedingly

brittle so that they can be powdered in a mortar. This renders them unfit for use in construction work or in chemical apparatus or for anything of the kind, and technically they are compounds of little value.

Solid Solutions. We will now consider the solid solutions. If we make a mixture of copper powder and nickel powder, and heat

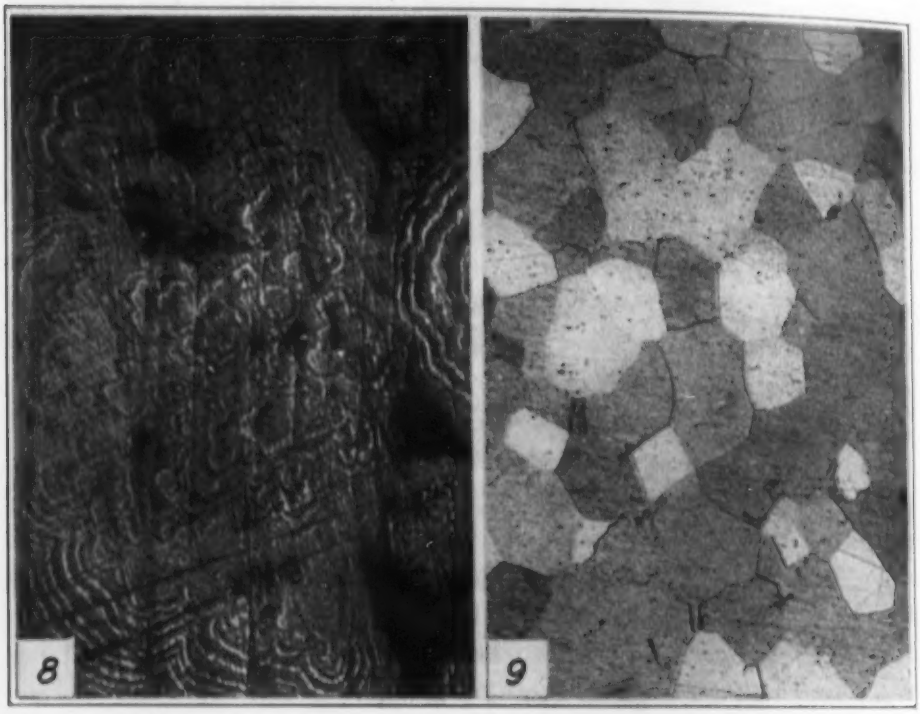

Fig. 8—Microstructure of Copper and Nickel as Deposited. Fig. 9—Microstructure of the Same Material After Annealing.

this mixture to a certain temperature, we will see that nickel and copper diffuse in each other, and form a solid solution. This is illustrated by photomicrographs Figs. 8 and 9. Fig. 8 shows the cross section of a copper wire, which was electroplated with nickel, then with copper; again with nickel and copper and so forth. This wire was then heated up to about 1470 degrees Fahr. (800 degrees Cent.) for a short time, after which the structure was completely changed (Fig. 9). There is now only one kind of crystal, although some seem to be light and some dark, due to the influence of reflections from crystals which have been cut in different directions. They each contain the same amount of copper and nickel. This shows that there really is a certain force which

drives these metals to form solid solutions, and therefore they must be, from the standpoint of stability, a little more resistant than the pure metals are, though the difference is not great.

Fig. 10 will make it clear that in such alloys the affinity for other elements is less than we could expect from the rule of mixtures. If "a" is the affinity of nickel (A) to some acid solution, and "b" the affinity of copper (B), we would expect the alloys

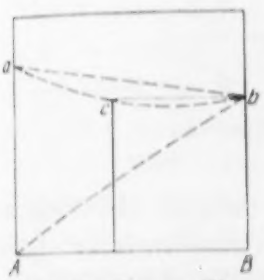

Fig. 10—Diagram Illustrating Chemical Affinity of Solid Solutions.

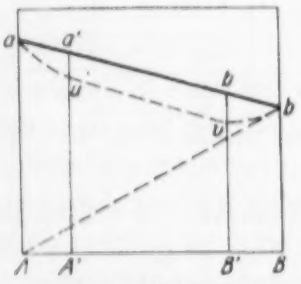

Fig. 11—Diagram Illustrating Chemical Affinity of Limited Solid Solutions.

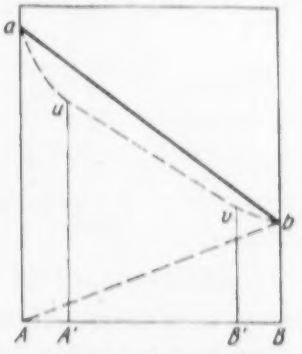

Fig. 12—Diagram Illustrating Another Case of Chemical Affinity of Limited Solid Solutions.

which form solid solutions to have an affinity on the line "a-b". Actually the affinities of the alloys are all lower than this line shows, and therefore the alloys have a greater stability. The energy of formation of the solid solution has to be subtracted, which makes the alloys from "c" to "b" a little more stable than even the pure metal B. Therefore, this is the second reason for using those alloys which form solid solutions, and it is also known that they have very good mechanical properties.

In Figs. 11 and 12 the formation of solid solutions is indicated to a certain extent. For example, silver is an element which when added to copper is taken up only in small amounts. The addition of enough silver to exceed the saturation point produces free crystals of silver (b) which will be present in copper (A). In the case of Fig. 11, from "v to b," the affinity of the alloys for another element will be a little lower than that of pure (B) while in the case of Fig. 12 it will be a little higher, though better than we would expect from the rule of mixtures.

Thermochemical Behavior. By again employing thermochemistry to study this problem, we get an idea of the quantitative change in stability by the formation of a solid solution. Not many

numerical data are available so far, but they are sufficient to show that the heat of formation of solid solutions is comparatively low. This indicates a quite apparent and well proved increase of stability of solid solutions, though, on the other hand it cannot be very great.

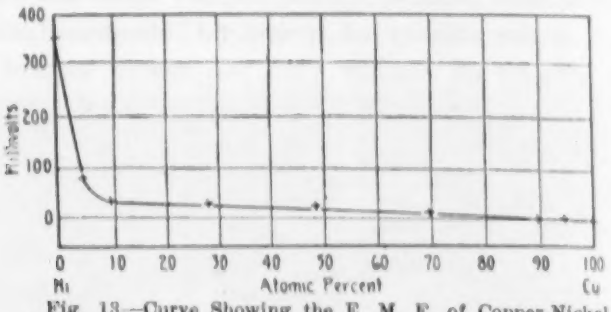

Fig. 13—Curve Showing the E. M. F. of Copper-Nickel Alloys.

Electrochemical Behavior. We find the data of electrochemistry very instructive. Fig. 13 gives the electromotive force of the copper-nickel alloys. Copper is nobler than nickel and has the lower solution pressure. The electromotive force of the series of solid

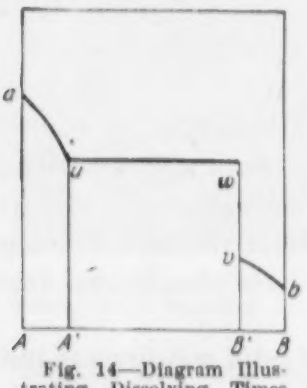

Fig. 14—Diagram Illustrating Dissolving Times of Alloys with Limited Solubility.

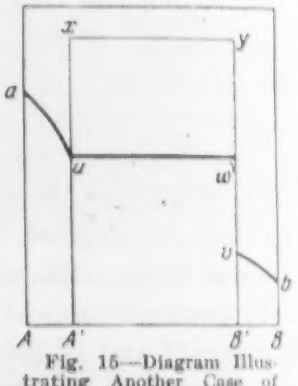

Fig. 15—Diagram Illustrating Another Case of the Dissolving Times of Alloys with Limited Solubility.

solutions does not follow the straight line (which would mean the rule of mixtures) but follows a curve, proving that the solid solutions are all electrochemically more noble than would be calculated from the rule of mixtures.

In cases of limited miscibility, Fig. 14 in starting from metal (A) only a limited amount of (B) will be taken up in solid solution. The affinity of (A) for nonmetallic reagents will decrease following the line "a-u" until we reach the saturated solid solution. Beyond this point we will not have the value w, of the second solid

solution, which is better, but the value u, and for the whole row of alloys we have the line "a-u-w-v-b."

Kinetics—Temperature Effect

Now, if we turn to the kinetics of the problem, we must consider first the influence of temperature. Here again, temperature has the same effect that it has on pure metals; the higher the temperature the more rapid will be the chemical reaction of the metals with the nonmetallic elements.

Catalytic Effect. Further we have the influence of a catalytic agent to consider. Any addition which is made to our alloys which is not taken up by the metals themselves to form solid solutions, will form impurities between and in the crystals. We can never tell in advance if such a heterogeneous impurity will have a catalytic influence on the corrosion or chemical activity of the alloy and therefore such an effect is to be avoided by making only additions, if any are necessary, which are taken up in solid solution. Thus we see the same thing for the third time.

Electrolytic Influences. The case of the iron sluice gate, which was referred to before, having some parts of bronze or copper, is an example of the electrolytic influence on corrosion. Another example of this effect is iron or steel containing an appreciable amount of copper or more than enough to form the saturated solid solution. The excess copper exists in the iron or steel as free copper crystals, which may start a local electrolytic corrosion, and cause the steel to corrode rapidly. Still more instructive is the enormous increase in the rate of corrosion of aluminum by the addition of tin, which is present in the alloy as free tin, or by the addition of mercury, which is present as an aluminum-mercury compound of unknown composition. Therefore, we see again, that an addition which is not taken up in solid solution, is generally to be avoided.

If we revert to solid solubility to a limited extent, and now consider not the statics but the kinetics of the reaction we will have the phenomena of Fig. 15. The curve is somewhat similar to that of Fig. 14. Beginning with the pure metal (A), the velocity of attack at first falls on account of the decreased affinity of the solid solutions. Passing the point "u" and entering the intermediate field between the two saturation points, we find the electrolytic effect on the corrosion velocity brought out in a most striking manner. Not only does the velocity of corrosion not follow the straight

line "u-w," but it will be very much greater—say "x-y." This large increase is observed as soon as we add more of (B) than is taken up in solid solution by the metal (A), on account of the presence of two different kinds of crystals and the corresponding formation of local galvanic elements.

Influence of a Protecting Layer. Next we have to consider the formation of a protecting layer on alloys. If we have pure iron at a high temperature and in the presence of air it will form an oxide layer on the surface which will protect it for a certain time against corrosion or oxidation. We have the same with chromium. Chromium, if it oxidizes, forms the oxide Cr_2O_3. Iron can form two oxides, first FeO and then Fe_2O_3. If we expose an iron-chromium alloy, or chromium steel to a high temperature FeO and Cr_2O_3 will first be formed. Now the chemist will tell us that if we melt these two together, they form a double oxide which is much more stable and which has the formula of $FeO.Cr_2O_3$ or $FeCr_2O_4$. It therefore would always contain two atoms of chromium and one iron, together with oxygen. Actually we do not have chromium steels with such a high chromium content—two chromium and one iron—because commercial steels contain more iron. If we have more iron present, it will oxidize to form ferrous oxide and ferric oxide, and these two will form a more stable double compound of ferric-ferrous oxide; magnetic oxide $FeO.Fe_2O_3$ or Fe_3O_4.

These two compounds of iron oxide and chromium oxide can be written in an analogous manner: Cr_2O_4Fe; Fe_2O_4Fe. The chemists often do write them that way, and they are really quite parallel. They are isomorphous and form solid solutions in all proportions. Therefore, if these double oxides exist together, the product is more stable than either is separately. So a normal chromium steel would form those two oxides and their solid solutions with each other of the formula $(Fe,Cr)_2O_3.FeO$, in which the ratio of chromium to iron is the same as in the steel. From our previous discussion it is clear that the space lattice of the oxide which is formed on chromium steel is, by three steps, more stable than the oxide of iron or chromium alone would be. If we add nickel, we would have a still more stable space lattice of the three oxides, having the formula $(Cr,Fe)_2O_2.(Fe,Ni)O$. Of course, I think we do not know at the present time how that space lattice is made up; it may be even a regular one. But whatever the space lattice is, it must be more stable.

The presence of a second structural constituent in a steel, such as carbide crystals or even free copper, can now be shown to be harmful, because under these circumstances it is clear that the protective oxide layer cannot be continuous. Wherever these crystals occur, the coating will be discontinuous because the oxide which might form, would be different from that which covers the main body of the steel. In effect, the coating is left full of holes,

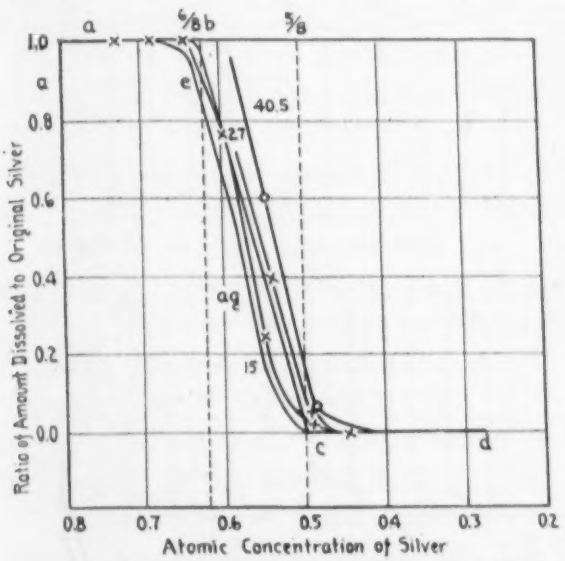

Fig. 16—Curves Showing Extraction of Gold-Silver Alloys with Nitric Acid. (Tammann.)

where the chemical action can proceed. This again, for the fifth, time, shows that it is preferable to use alloys which contain only one kind of crystal and which are able to form a continuous protective coating of a constant composition. Such alloys must be solid solutions.

Influence of Space Lattice. We shall consider, finally, the "reaction limits" in solid solutions, which are shown by the experiments of Tammann in Germany. He studied first the behavior of the silver-gold alloys when treated with nitric acid. Fig. 16 gives as abscissae the atoms of silver per 1.0 total. Beginning with 1.0 of silver at the left side, we have 0.9, 0.8 and so on, until we have 0.0 of silver or 1.0 of gold, at the right side. In the figures, only that portion between 0.8 and 0.2 of silver is included. As ordinates we find the amount of the total silver present that was dissolved out of the alloys by the nitric acid. Beginning from the gold side, he found of course that no (0.0) silver was dissolved, and even with

increasing additions of silver until an appreciable amount was present, the gold would not give up any of the silver present, even after boiling the alloy for weeks in nitric acid. On reaching concentrations of 0.5 in molecules—that means equal amounts of silver atoms and gold atoms—Tammann suddenly got an increasing amount of silver dissolved. This held until he had reached pure

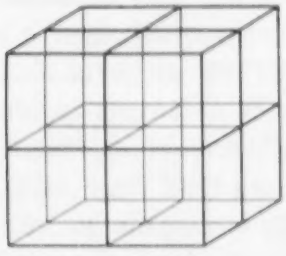

Fig. 17 0/8

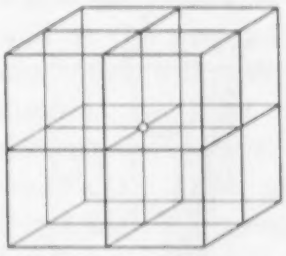

Fig. 18 1/8

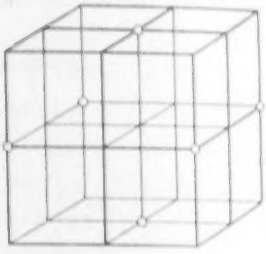

Fig. 19 2/8

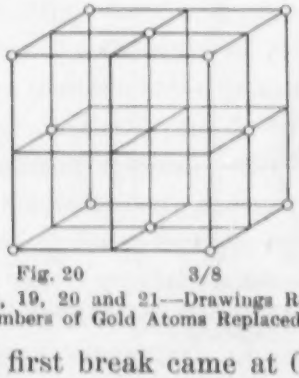

Fig. 20 3/8

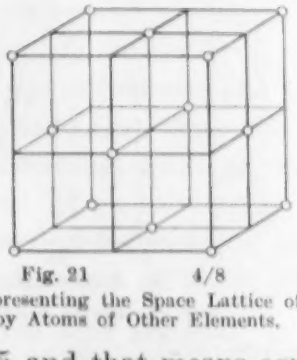

Fig. 21 4/8

Figs. 17, 18, 19, 20 and 21—Drawings Representing the Space Lattice of a Gold Crystal with Varying Numbers of Gold Atoms Replaced by Atoms of Other Elements.

silver. The first break came at 0.5 and that means equal amounts or 4/8 of silver and gold, and the second break came at 0.625, which means three atoms of gold to five atoms of silver.

Experimenting with other alloys which form solid solutions, Tammann always found that the reaction limits or breaks came at 1/8 and 2/8 atom-parts of the second constituent.

On what basis are such reaction limits to be explained? All those metals tested come in the cubic system, the lattice unit of which is the cube with eight corners. Fig. 17 shows eight elementary gold cubes as part of the space lattice of a gold crystal. Now if we replace 1/8 of the gold atoms by silver atoms, we will have a silver atom occupying one corner of each cube, Fig. 18. Within that gold lattice such an atom might be absolutely protected. For example, it is not possible for an atom of chlorine to go through the space lattice, because a phalanx of gold stands like a wall preventing the reagent from reaching the atom of silver or other protected atom. In Fig. 19 we have the 2/8 ratio so that each cube will have two

corners occupied by silver atoms. Now let some kind of chemical reagent move to attack. For example if the crystal is gold with 2/8 of magnesium, the chlorine can attack first on the surface and then along the cube diagonal to take that next magnesium atom. That is what it really can do and by crossing all the cubes by the diagonal it takes all the atoms of magnesium out. What remains is a very weak kind of a space lattice of gold atoms much like a wooden frame construction which has had parts taken out, causing the whole thing to break down before a mild wind. We can readily crush such crystals with our fingers. A more complicated reagent, like the radical NO_3 of nitric acid or SO_4 of sulphuric acid, the atoms of nitrogen or sulphur dragging along a long tail of oxygen atoms, may not be able to get through the diagonal of the cube, but it might get through on the diagonal of a face. In this case, the reagent would reach a detachable atom only if the ratio is 4/8. This is illustrated in Fig. 21. Therefore we will find that the more complicated radicals will need 4/8 before they can continue their destructive work throughout the space lattice.

Fig. 20 shows 3/8 replaced, which is really not symmetrical. We will find in the first lattice plane a ratio of 4/8 and in the next plane a ratio of only 2/8; in the third, again 4/8 and so on. Such an arrangement is not symmetrical. Generally 3/8 or 5/8, is not a characteristic concentration.

This is a general review of what Tammann did and while his conclusions may not be universal in application, they are vital to the proper understanding of those cases to which they do apply. In all such solid solutions you find 1/8, 2/8, 4/8, 6/8 and 7/8 as critical concentrations.

We know for example, that in making gold alloys, we alloy gold with copper to make it hard and mechanically resistant. The goldsmith likes to treat the alloy with nitric acid, which dissolves out the copper atoms from the surfaces, and leaves the piece looking absolutely like pure gold. This is because on the surface there will be only gold atoms and they will reflect only yellow light. If a ring treated in this way is worn for several years it becomes more and more reddish, because the atoms of gold will be rubbed off and the underlying copper atoms will be exposed. The metal can then be again etched with nitric acid and the cycle repeated. This enables the nitric acid to enter deeper and deeper into the ring.

This is a combined chemical and mechanical action, and by it we can finally break down the whole ring. This shows where the problem of abrasion becomes very important, and how it is to be explained.

This type of protection of the space lattice can become operative, of course, only if we have two different kinds of atoms in the

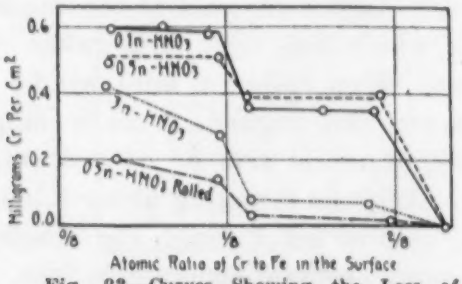

Fig. 23—Curves Showing the Loss of Chromium from Iron-Chromium Solid Solutions by Nitric Acid Attack.

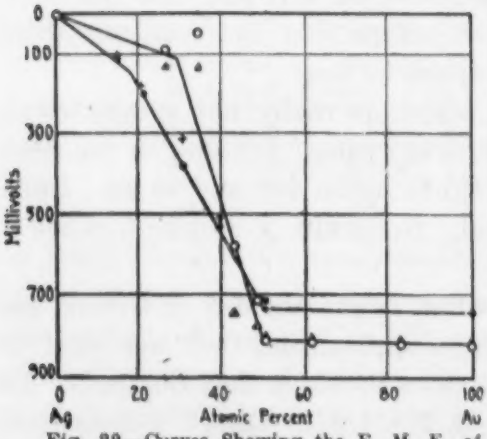

Fig. 22—Curves Showing the E. M. F. of the Gold-Silver Alloys at Room Temperature. (Tammann.)

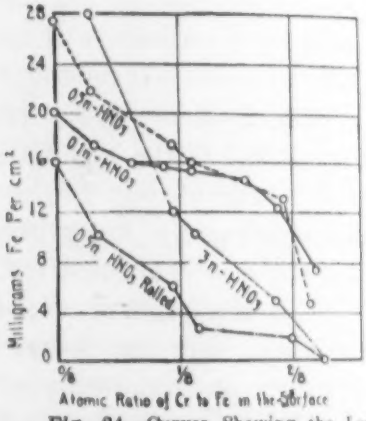

Fig. 24—Curves Showing the Loss of Iron from Iron-Chromium Solid Solutions by Nitric Acid Attack (Grube and Fleischbein).

space lattice. That means again that we have a solid solution in which one kind of atom is dissolved in the space lattice of the other kind. Therefore, for the sixth time, we see the importance of solid solutions.

Electrochemical measurements also bring out the same feature. Fig. 22 shows the solution pressures of the alloys of gold and silver. Breaks occur at 1/8, 2/8 and 4/8. The same measurements were made at a temperature of 320 degrees Cent. and this time no break at all was observed. And why? It is because at that high temperature we have a high diffusion velocity. If one kind of atom is removed by the chemical reagent, new atoms of that same kind will

Table II

Chemical and Galvanic Reaction Limits, Expressed as Parts of the Inactive Metal (Tammann)

Alloy Components	Reaction Limits					
Ag-Au	...	2/8	4/8	...	...	Mol Au
Cu-Au	1/8	2/8	4/8	...	...	Mol Au
Fe-V	...	...	4/8	...	...	Mol V
Mn-Ag	...	...	...	6/8	...	Mol Ag
Mg-Ag	...	...	...	...	7/8	Mol Ag
Zn-Ag	...	2/8	...	...	...	Mol Ag
Zn-Au	...	2/8	4/8	...	...	Mol Au
Pd-Au	...	...	4/8	...	...	Mol Au
Pd-Ag	...	...	4/8	...	...	Mol Ag

diffuse at once from the interior to the surface, to produce an equal distribution of all the atoms. If we have a high temperature, such a condition is possible by diffusion.

We have learned so far what happens if we start with a resistant metal and add a less noble metal. This gives an absolute protection until the atomic concentration of 1/8, 2/8 or 4/8 is reached.

We may next consider what happens if we start with an easily corrodible metal and add a second metal which is chemically more resistant. For example, we may start with iron and add chromium in an attempt to make an acid resisting steel. Chromium is selected because it is resistant to nitric acid. In nitric acid it forms a chromium oxide in preference to chromium nitrate, and the oxide is not soluble in nitric acid. Figs. 23 and 24 show the results of some experiments which were made by Grube and Fleischbein in Stuttgart. E. C. Bain informs me that he made some similar experiments with about the same results. The results show that if we alloy chromium with iron in increasing proportions we will find the rate at which chromium is dissolved from the alloy by nitric acid to remain practically constant; but that as soon as we have more than 1/8 atom of chromium per total, we will find a sudden decrease in the amount of chromium dissolved. This rate will remain constant until we pass above 2/8 and at that concentration the solubility becomes zero. The ratio 2/8 atoms corresponds to a content of 24 per cent chromium, which explains why this particular composition plays such an important part in the practice of acid resisting steels.

Fig. 24 gives the amount of iron which is dissolved in the same way. Iron is closely similar to chromium, though the con-

stancy below 1/8 and the break at 1/8 is not as sharp as with the chromium. From these experiments we learn that if we start with an attackable metal and wish to give it a higher resistivity, that this addition should be taken up in solid solution by the first metal. Such an alloy will reflect the special properties of the added element and confer acid or corrosion resistance to the alloy.

Practice

Let us now turn to the practical side of our problem. If we leave out of consideration the precious metals, like silver, gold, platinum and so on, and the semi-precious high melting metals, like molybdenum, tungsten and tantalum, we have, as mentioned before, only eight metals which can be used on a major scale as the chief constituents of alloys. All the rest of the metals are chemically nonresistant, like sodium, or are brittle, like titanium or antimony, or are rare and expensive, like the metals of the rare earth group.

General View

These eight useful metals are given in Table III in the first row. The other parts of the table show the amounts of the different added elements taken up in solid solution by each of the eight first mentioned metals.

These eight metals can be divided into three groups: (1) Aluminum and magnesium; (2) zinc, lead and tin; (3) iron, nickel and copper. The table shows the very important property possessed by iron, nickel and copper of forming solid solutions. For example, iron will take up vanadium to any extent, right up to pure vanadium. The same is true of chromium, manganese, cobalt and nickel.

Iron will also take up 33 per cent aluminum in solid solution—that is used for the calorizing process. Silicon is taken up to 14 per cent, that is greatly used to make acid-resisting alloys. Molybdenum will be much used for the same reason and also tungsten. This indicates a big field still to be developed, to form acid resisting alloys. Nickel is even better than iron. It takes up chromium, vanadium, manganese, iron, cobalt and copper in any amount, and tin, zinc and aluminum to a great extent, to form solid solutions. Copper will also take up 100 per cent of manganese, nickel, and gold and large amounts of zinc, tin and aluminum. If we compare these metals with the three

Table III

Solid Solution Formation of the Technically Important Metals

The figures give the limits of solubility in per cent
O indicates insolubility and 100 complete solubility

		K																							
		Na	Ca																						
		Li	Ba	Mg	Al	Ce	B	C	Si		Ti	V	Cr	Mo	W	Mn									
Light Metals	Al	(3.5)	0	(11)	.....	<0.5	0	0	(1.5)		0	.....	.....	.....	.....	<0.1									
		Li																							
Light Metals	**Mg**	.....	.....	.....	(10.6)	0	.....	.....	.....		.....	.....	.....	.....	.....	.....									
Low-melting, Heavy Metals	**Zn**	.....	.....	.....	0.5	.....	.....	.....	.....		.....	.....	.....	.....	.....	.....									
Low-melting, Heavy Metals	**Pb**	0	0	0	.....	.....	.....	.....	.....		.....	.....	.....	.....	.....	.....									
Low-melting, Heavy Metals	**Sn**	.....	.....	.....	.....	.....	.....	.....	.....		.....	.....	.....	.....	.....	.....									
High-melting, Heavy Metals	**Fe**	.....	.....	.....	33	13	0.08	(1.5)	16		3	100	100	28	10	100									
High-melting, Heavy Metals	**Ni**	.....	.....	.....	15	*	.....	.....	7		*	100	100	33	5	100									
High-melting, Heavy Metals	**Cu**	.....	.....	.....	8	.....	.....	.....	2		.....	.....	.....	.....	.....	100									
		Fe	Co	Ni	Cu	Ag	Au	Pt	Zn	Cd	Sn	Pb	Bi	Sb	As										
Light Metals	Al	<0.1	.....	<0.1	(5.6)	.....	.....	.....	8	.....	.....	.....	.....	<0.5	.....										
Light Metals	**Mg**	.....	.....	.....	2	.....	.....	.....	2	100	0	.....	.....	.....	.....										
Low-melting, Heavy Metals	**Zn**	.....	.....	.....	3	.....	.....	.....	.....	(2.5)	.....	.....	.....	.....	.....										
Low-melting, Heavy Metals	**Pb**	.....	.....	0	0	.....	.....	.....	.....	6	6	.....	8	0	0										
Low-melting, Heavy Metals	**Sn**	.....	.....	.....	0	.....	.....	.....	.....	0	.....	1	6	8	.....										
High-melting, Heavy Metals	**Fe**	.....	100	100	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....										
High-melting, Heavy Metals	**Ni**	100	100	.....	100	.....	.....	.....	35	.....	15	.....	.....	.....	0										
High-melting, Heavy Metals	**Cu**	.....	.....	100	.....	4.5	100	.....	36	.....	13	0	.....	.....	0										

NOTE: Figures in brackets give solubility at elevated temperatures.
Asterisk indicates possible additions, constitution not entirely known. Dotted lines indicate no technical importance.

low melting metals we will find an absolutely different behavior. Tin will take up a little lead and bismuth in solid solution; lead dissolves only a little cadmium, bismuth and tin; and zinc takes up only a little aluminum and a few per cent of copper.

From this it is clear why it is that no one has ever developed acid resisting zinc alloys. Such a development will be absolutely impossible for all future time. Chemical reagents which zinc itself will not stand, zinc alloys also will not stand, because the nature of the crystals cannot be changed. This could be done only if they were able to take up some additions in solid solutions, which they cannot. Therefore, in all the zinc alloys we will find present these same zinc crystals, in some cases slightly modified by the small amount that they take up in solid solution but which will not be large. Therefore in all these alloys the zinc crystals will behave much as they would if they were alone and at times even worse, because there may be an electrolytic influence due to the presence of two different kinds of crystals. So all zinc alloys, if they differ from zinc in chemical behavior, can only be worse.

Aluminum, and this is also a sad chapter of metallography, has only a small possibility of taking up other elements in solid solution. It takes up a little copper, the others do not amount to anything. Only zinc is taken up in greater amount—but zinc is not a noble metal in itself and it cannot give aluminum acid resisting properties.

Magnesium, I am sorry to say, does not behave in any way better than aluminum.

For all future, if we do not want to consider the noble metals, the acid resisting metals will all be built up on the basis of iron, nickel or copper. Iron, which by itself has a low stability, and is even worse than zinc, can be successfully utilized only on account of its ability to take up other elements in solid solution and so transform the metal into a good acid resisting alloy. Nickel and copper also take up other elements in solid solution and, therefore, these three metals can be developed to form acid resisting alloys.

Special Acid Resisting Alloys

Fe-Ni-Cr Alloys. Fig. 25 shows a diagram of chromium-nickel-iron alloys. Here are plotted the different alloys which

are used in practice. On the left corner is iron and on the right is nickel. From the chromium-nickel steels we have a continuous transition to the nickel alloys. The alloys above the line of 40 or 50 per cent chromium are too brittle. It is on account of this brittleness that chromium cannot be the chief constituent of an alloy. Below that line practically all the alloys are useful. If

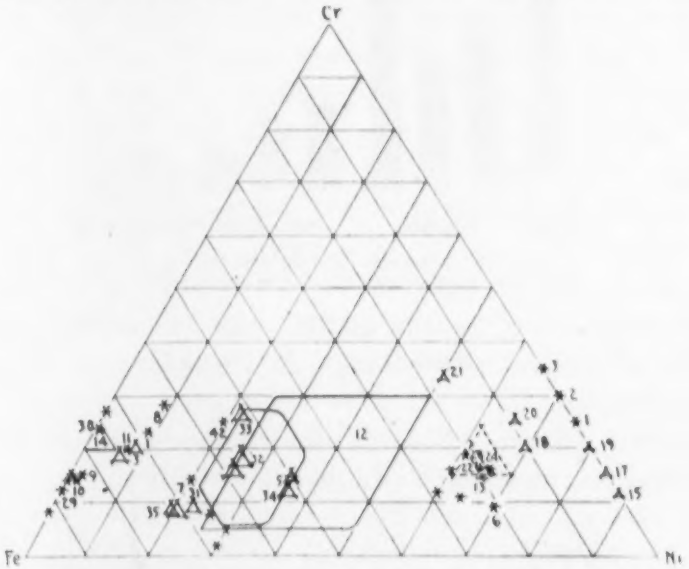

Fig. 25—Diagram Showing the Technical Alloys of Iron, Chromium and Nickel.

one were to ask which of all these alloys is the best, no definite answer could be given, because he really could not say any alloy is the best. It depends upon which kind of solution is to be used and which kind of attack the alloy has to stand. In nitric acid of some particular concentration, one special alloy may be the best, but if the acid is stronger another will be better. If the temperature is higher, a third one will be better. As a rule the alloys rich in chromium and iron are better to nitric acid. Those rich in nickel are better in sulphuric and hydrochloric acid.

Fig. 26 shows, as an example, the resistance of these alloys to nitric acid. At the left is iron, then come 4 per cent nickel, 9 per cent nickel, and finally 20 per cent nickel, which is worse than pure iron. This proves that the resistivity is not always proportional to the amount of the addition. Then come chromium, then iron alloys with 13, 17, and 40 per cent of chromium, the latter of which is very good. The last two alloys have chromium

and nickel combined and the attack of these alloys is zero, in both cases.

From what has been said before, we will understand that the addition of nickel alone or of chromium alone will not give as good

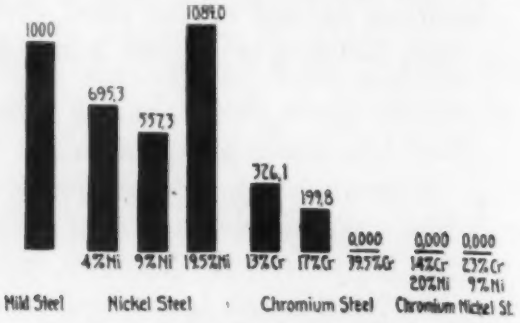

Fig. 26—Diagram Showing the Loss of Weight of Various Steels in Cold 1 Per Cent Nitric Acid.

alloys in many cases, as the addition of these two together, because the protective oxide which is then formed has a higher chemical stability.

Fe-Cu-Ni Alloys. Fig. 27 shows the influence of copper, which is really interesting. Copper alone will be taken up by the

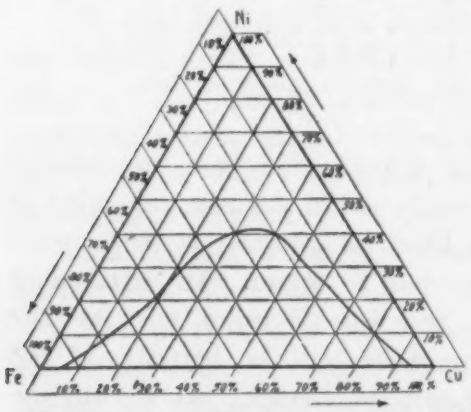

Fig. 27—Curve Showing the Effect of Nickel on the Solubility of Iron and Copper.

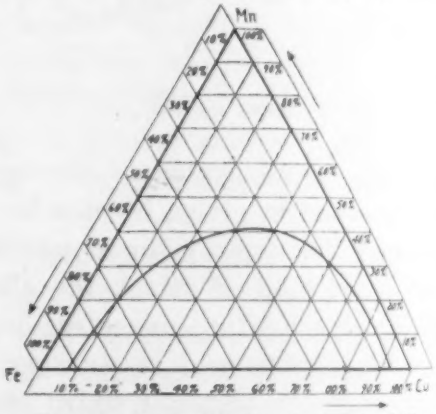

Fig. 28—Curve Showing the Effect of Manganese on the Solubility of Iron and Copper.

iron crystals only up to about one per cent, in ordinary steels. Therefore, if we add less than one per cent, and treat the steel in the right way, this one per cent completely enters the iron crystals. This action gives an alloy whose resistance is increased as compared to pure iron, but as soon as a little too much is added, free copper crystals are present in the steel, and electrolytic corrosion is started.

If we add nickel together with the copper, then nickel will

help the copper to dissolve in the iron crystals. With increasing additions of nickel, increasing amounts of copper will be soluble in the iron, as is shown by the solubility line which runs from the iron to the copper corner, and divides the whole ternary diagram up into two parts. Above that line within the field of homogeneous solid solution, the addition of copper and nickel produces an increase in resistivity. Below the line is a field in which there are two different kinds of crystals which will be clear to those who are familiar with ternary systems. The iron will predominate, but there will also be some copper crystals. Copper-nickel steels, within the limits of the two-phase field, will always have copper crystals present, the composition of which is given on the right of the saturation curve. An alloy in the heterogeneous field which is rich in copper, will always contain some free iron-rich crystals, which will corrode. Therefore such an alloy will be very bad. But on the other hand, an alloy above the saturation line, such as one with about 20 per cent nickel and copper, could be very good, because the iron is protected to a great extent by the presence of nickel and copper. The saturation line shows that the more nickel we add, the greater is the amount of copper absorbed by the iron crystals. If we have enough nickel present, we can also add a large amount of copper.

Fe-Cu-Mn Alloys. The same is the case if we have manganese present, as Fig. 28 shows. On the left we have iron, and on the right copper, as before. On the top is manganese. If we add enough manganese, 10 or 15 per cent, the amount of copper that is dissolved by the iron crystals increases. So the Fe-Cu-Ni and Fe-Cu-Mn alloys open to us a very important field which is worth further investigation.

Fe-Si Alloys. Fig. 29 gives us the influence of silicon on the acid resistivity of iron. The diagram gives the amounts of metal lost by boiling in 5 per cent hydrochloric acid for stated times (10, 20 and 30 hours), for increasing additions of silicon. The losses from pure iron or from iron with small additions of silicon would be far above the limits of the curves. The alloy with 11 per cent silicon will be much better, but beginning with 14 per cent, at 15, 16 and 17 per cent we obtain splendid protection. Further additions will not make much difference. The critical concentration is 14 per cent, which is again 2/8 atoms exactly.

Finally we have molybdenum and tungsten as additions which are taken up by iron in solid solution to a great extent. Molybdenum itself is highly resistant to hydrochloric acid and is fairly so to sulphuric acid. (See Table IV.) I have experimented a good deal with the chemical resistivity which molybdenum imparts to those metals by which it is taken up in solid solution. (Zeitschrift f. Metallkunde (1925), vol. 12, pp. 310-315.)

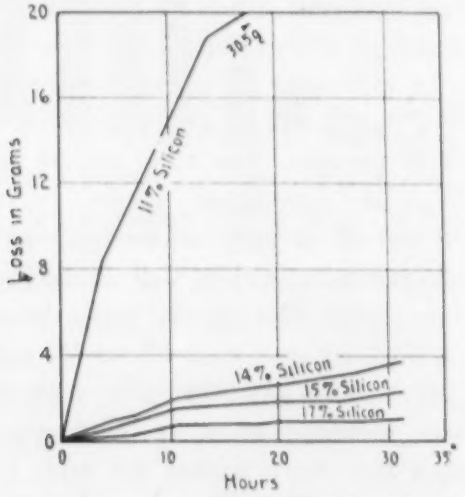

Fig. 29—Curves Showing the Loss of Weight of Iron-Silicon Alloys in Boiling 5 Per Cent Hydrochloric Acid.

The result was that molybdenum, as an addition to iron, cobalt, nickel and their mutual alloys increases their resistance, especially to hydrochloric acid and sulphuric acid. These results encouraged W. Rohn (Director of W. O. Heraeus, Hanau) to make extensive experiments on a large scale and he was able to confirm the beneficial effect of molybdenum additions. In the same way the Krupp works added molybdenum to their famous chromium-nickel steel called V2A, which increased its resistivity against nitric, sulphuric and hydrochloric acids. Tungsten is similar in action and should be much more used to make steels of special chemical resistivity.

After having considered all these examples of iron-base alloys, we do not need to extend the discussion to other alloys which have nickel or copper as a base. It will be simple enough now by applying the same principles to develop acid resisting alloys of nickel and copper. Of course they will be more expensive than the steels, but they ought to prove of great value in special cases

Table IV

Loss of Weight in g/dm² of Alloys (Determined by W. Rohn)

Name	Composition											Nitric Acid 10%		Sulphuric Acid 10%		Hydrochloric Acid 10%		Acetic Acid 10%		Phosphoric Acid 10%		Treatment
	Fe	Ni	Co	Cu	Cr	Mo	W	Mn	Si	Al	C	24 h. cold	1 h. hot	24 h. cold	1 h. hot	24 h. cold	1 h. hot	24 h. cold	1 h. hot	24 h. cold	1 h. hot	
	100	....	....	....	....	....	....	....	....	....	....	.....	36.7	0.24	15.6	0.12	21.0	0.21	0.76	0.14	12.3	Annealed
	....	99.5	....	....	....	....	....	....	....	....	....	0.50	9.07	0.01	0.02	0.04	1.51	0.004	0.604	0.004	0.004	Annealed
	....	....	99.5	....	....	....	....	....	....	....	....	10.7	27.3	0.06	0.30	0.08	2.3	0.04	0.15	0.06	0.7	Hot Rolled
	....	....	....	100	....	....	....	....	....	....	....	2.5	20.8	0.010	0.018	0.07	0.05	0.004	0.025	0.017	0.014	Annealed
	....	....	....	....	100	....	....	....	....	....	....	0.013	0	0.01	45	77.4	150	0.13	0.03	0	0	Slowly Cooled
	....	....	....	....	....	100	....	....	....	....	....	5.2	1.8	0.06	0.015	0.61	0.0015	0.02	0.007	0.03	0.009	Hot Rolled
	....	....	....	....	....	....	100	....	....	....	....	0	0.06	0	0.01	0	0.01	.....	.....	.....	.....	Hot Rolled
	....	....	....	....	....	....	....	....	....	....	....	0	0	7.5	32.	6.5	27	0.03	0.024	0.04	2.44	Annealed
V1M	84	....	....	16	....	....	....	....	....	....	....	0	0.03	0.7	15.6	0.19	4.5	0	0.03	0	0.03	Rolled
	82	2	....	15	....	....	....	0.4	0.5	....	0.15	0	0	6.5	76	56	94	0	0	0	0	Annealed
V2A	74	....	....	25	....	....	....	....	1	....	....	0	0	0.03	2.53	0.25	1.55	0	0.05	0	0.05	Annealed
Ferron	71	8	....	20	....	....	....	0.26	0.29	....	0.22	0.01	0.01	0.03	0.08	0.26	0.96	0.08	0.35	0.006	0.1	Rolled
Ao	50	35	....	15	....	....	....	....	....	....	....	0.24	0.05	0.15	0.05	0.10	1.20	0.02	0.07	0.04	0.03	Annealed
B	....	88	....	11	....	....	....	1	....	....	....	0.37	0.9	0.02	0.05	0.10	1.20	0.02	0.07	0.04	0.03	Annealed
C Chro-	20	64	....	15	....	....	....	1	....	....	....	0.19	0.02	0.03	0.11	0.14	1.97	0.016	0.01	0.008	0.062	Annealed
Co man	10	69	....	20	....	....	....	1	....	....	....	0.01	0.02	0.14	0.09	1.44	1.66	0.005	0.005	0.01	0.11	Rolled
E	....	79	....	20	....	....	....	1	....	....	....	0.02	0	0.01	0.14	0.03	0.68	0.002	0	0.004	0.051	Annealed
B4M Con-	16	50	....	33	....	....	....	1	....	....	....	0.01	0	0.02	0.01	0.09	3.51	0	0	0	0.008	Annealed
B7M tra-	18	61	....	15	....	4	....	2	....	....	....	0.013	0.05	0.02	0.013	0.043	0.027	0.008	0.002	0.008	0.005	Annealed
B6W fid	15	61	....	15	....	7	....	2	....	....	....	0.01	0	0.01	0.02	0.01	0.02	0.002	0.006	0.0012	0.16	Annealed
	16	61	....	15	....	....	6	2	....	....	.5	0.08	0.01	0.02	0.02	0.03	0.18	0.0025	0.002	0.02	0.03	Annealed
	17	61	....	15	....	....	....	2	....	....	....	0.26	0	0.05	0.22	0.26	6.5	0.014	0	0.068	0.016	Annealed
	....	....	90	....	10	....	....	....	....	....	....	9.5	17.3	0.012	2.4	0.06	1.2	.....	.....	.....	.....	Annealed
Constantan	....	40	....	60	....	....	....	....	....	....	....	0.24	7.6	0.01	0.012	0.073	0.29	0.002	0.004	0.002	0.008	Annealed
Monel	2.5	68	....	27	....	....	....	2.5	....	....	....	0.02	0.73	0.012	0.004	0.04	0.23	0.004	0.004	0.002	0.01	Annealed

where the weight of the metal necessary is not great and a special high quality is wanted.

Of course, a further great development is possible and has been partly accomplished by starting from iron or nickel or copper and making more than one addition at a time resulting in ternary, quaternary and more complex alloys. The principal limitation will be the necessity of staying below the saturation

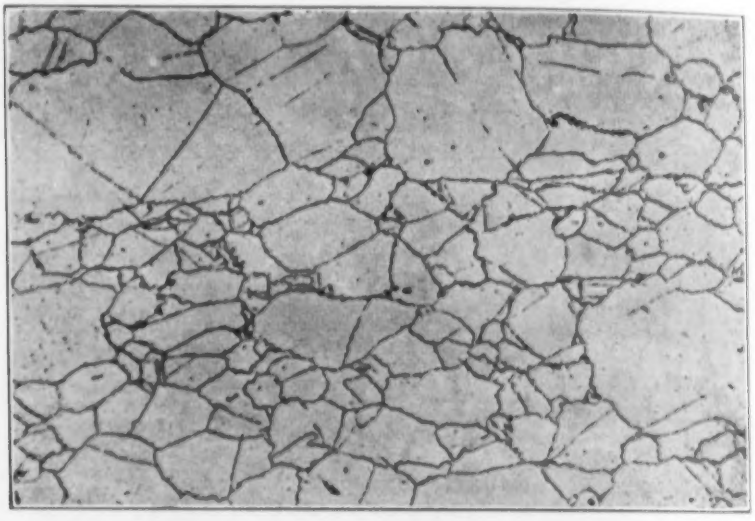

Fig. 30—Photomicrograph of an Alloy of Iron, Chromium, Nickel, Vanadium, Manganese, Titanium, Tungsten and Molybdenum, in Solid Solution Form.

point of the solid solutions. These limits of solubility are affected by the additions which are made and will have to be investigated in every case. This means that the saturation lines of the combined systems will have to be determined. Within the fields of the solid solutions we can now combine a great number of additions and so form innumerable new alloys.

Again and again a one-phase homogeneous structure characterizes all these resistant alloys, however complicated the composition may be. Fig. 30 gives the microstructure of an alloy which contains iron, chromium, nickel, vanadium, titanium, tungsten and molybdenum, but it does not show any one of these. Instead, there is only one kind of crystal which on etching shows the crystal boundaries developed. Every crystal contains all the metals present in the same amount, in solid solution.

Finally, as a further example, I would mention here the results of W. Rohn, published in Zeitschrift f. Metallkunde, 1927;

Table IV is condensed from the table which he published and shows the results obtained with steels and nickel alloys where a number of conditions are combined. I wish to mention the alloys B4M and B7M, which, by addition of molybdenum, have a resistivity for aqua regia which is equal to that of gold and nearly that of platinum.

Summary

In closing I shall give a short resumé, as follows:

First; If one wishes to develop commercial acid resisting alloys, he must start with iron, nickel or copper.

Second; If he make additions, he must choose elements which are taken up by these metals in solid solution.

Third; If he make additions which are not taken up in solid solution, he cannot hope to improve the chemical resistance of the alloys, but such additions might be made to improve some other properties, such as the magnetic, mechanical or electrical properties. But the best he can do with the chemical properties is to leave them unaffected.

Fourth; If additions are made which are taken up in solid solution, then to a great extent he will find that the product is improved in that specific protective action which is characteristic of the added element. For example, chromium will resist nitric acid very well, because it forms a hard resistant oxide. It follows, then, that chromium will impart this property to all those metals by which it is taken up in solid solution.

Fifth; If one wishes to develop an alloy which is resistant to some special reagent, then he should try to find a chemical compound of some metal and this chemical reagent which is not soluble in the reagent. Then by adding this metal to the one which is desired to be more resistant, he may have the luck to find that it is taken up by the latter in solid solution, and that under the influence of that reagent it forms a continuous coating without any holes and discontinuities. Then he will attain the effect sought.

Sixth; If we find that the chemical agent is attacking the alloy in use, we should not be discouraged, because a slight change in the chemical composition of the reagent—even the addition of some colloidal substance, which may seem quite unimportant, will

often produce a protective coating from one which otherwise would not be continuous. Being now continuous the new coating will protect. On the other hand, if a good protection has been discovered for some chemical reagent, we must not feel absolutely sure that it will persist because a slight difference in temperature or in the concentration of the chemical reagent might change the problem entirely.

Seventh; The last point is: we must never expect to find a permanently durable alloy which will be universally resistant to all reagents, but we may reasonably expect a very beautiful development of alloys, each of which has its own special application. Nor is it likely that we will find an alloy which will resist every kind of chemical reagent in the same way. According to the solubility or non-solubility of the different chemical compounds which may form on the surface, one alloy will be better for one reagent and another alloy will be better for a different reagent.

DILATOMETRIC ANALYSIS OF STEEL AND SOME RESULTS OF DILATOMETRIC HEAT TREATMENT

By R. W. Woodward and S. P. Rockwell

Abstract

The authors of this paper have shown that by the use of the dilatometer certain fundamental constants may be obtained. From these it is proposed to classify steels according to their proper quenching medium. Taking advantage of thermal hysteresis to lower the quenching temperatures is discussed. When this lower quenching temperature is used it is often possible to brine-quench normal oil-quenching steels to give superior results. When using the dilatometer, quenching at the completion of the transformation or point of re-expansion is obtained by the automatic signal, other fixed points on the dilatometric curve may be used to give greater depth of hardness at a sacrifice of toughness and grain size.

IN REGULAR heat treatment by dilatometric means a great many phenomena have been observed which indicate in a general way the different classes of dilatometric curves produced upon heating various types of steels. For instance, it is generally possible to indentify by the characteristics of the heating curve whether a particular steel should be water or oil-quenched. The purpose of this investigation was to study the dilatometric curves obtained on heating and cooling a uniform size of specimen of several commercial carbon and alloy steels, and to make a study of warping, microstructure, hardness and depth of hardness of a typical water-hardening and a typical oil-hardening steel when quenched from various definite points on the time-dilatation curve.

The dilatometer used in making these tests is shown in Fig. 1. This is a laboratory type instrument having a furnace with a heating zone 3 inches in diameter by 12 inches long and which produces autographically a time-dilatation curve. The specimen under study is supported entirely independent of the furnace so that all length changes observed are due to volume changes of the steel

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with the exception of a small expansion due to the quartz contact rods. For precise work correction can be made for the latter error but in this investigation the error was negligible for the purpose at hand.

The steel specimens used were all 6 inches in length by 1 inch in diameter cut from machined bars and had a small hole drilled

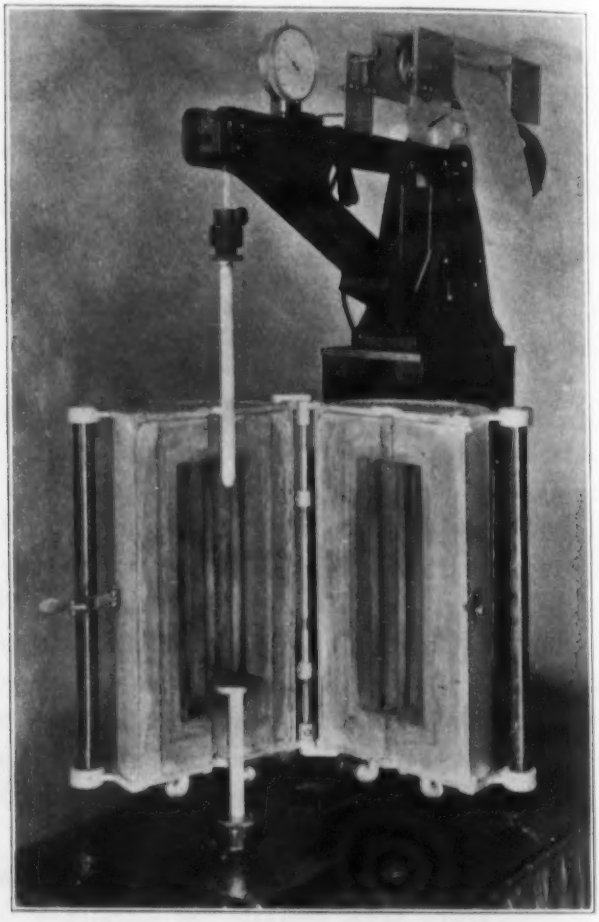


Fig. 1—Photograph of the Dilatometer Used in Making the Dilatometric Analyses Described in This Paper.

near the center for the insertion of an iron-constantan thermocouple. The latter was connected to a high-resistance galvanometer. Table I gives the compositions of the steels studied.

Heating and cooling curves were taken on all of these materials under as nearly uniform conditions as possible. The specimens were placed in the cold furnace and the same heating current was used in all cases. This rate of heating was such that the furnace

would reach 1800 degrees Fahr. from room temperature in about 2 hours if allowed to continue for that length of time.

For the usual type of steel the time-dilatation curve is as shown in Fig. 2. From A to B we have normal expansion of ferrite or alpha iron. The pen was reset to zero during this period in order to bring all of the curve upon the chart. At B expansion

Table I
Chemical Composition of Steels

No.	C	Mn	Si	PER CENT P	S	Ni	Cr	Va
1	0.21	0.35	...	0.010	0.025	...	....	...
2	1.01	0.26	0.19	0.019	0.018	...	tr.	...
3	0.90	1.68	0.13	0.017	0.007	...	0.18	...
4	1.00	0.51	0.15	0.026	0.018	...	4.22	...
5	0.29	0.63	0.24	0.021	0.031	3.16	0.76	...
6	0.40	0.54	0.22	0.024	0.038	3.33	0.24	...
7	2.14	0.29	0.14	0.019	0.022	...	12.23	0.15
8	0.36	0.26	0.04	0.019	0.022	0.10	13.18	...
9	0.99	0.27	0.19	0.019	0.019	...	tr.	...

stops and contraction begins denoting the beginning of the Ac transformation. This point is indicated by an automatic alarm on the dilatometer and a reading of the temperature was made coincident with the alarm. From B to C the loss in volume due to the alpha-gamma transformation continues as shown by the contraction, while from C to D nearly constant volume obtains until the solution of the carbides is complete. This "hold time" or period of nearly constant volume is quite characteristic of different types of steels and for steels which we know are sluggish, such as those containing chromium, is a considerable proportion of the entire transformation.

At point D another automatic alarm signal is given indicating re-expansion and the completion of the Ac transformation. In heat treament by this method quenching takes place at this signal but in this work the temperature was read and re-expansion was allowed to continue a short distance so as to determine the shape of the curve at this point. From D to X, at which point the furnace current was shut off, expansion of austenite takes place. Cooling at the normal furnace rate immediately starts and there is a period of austenite contraction from X to E where expansion again starts, marking the beginning of the Ar transformation. This point is also indicated by the automatic alarm and the temperature noted.

The increase in volume accompanying the gamma to alpha transformation continues from E to F when an additional signal is made, the temperature read and then the normal ferrite contraction allowed to continue for a short time.

Duplicate curves were run on separate samples and the two

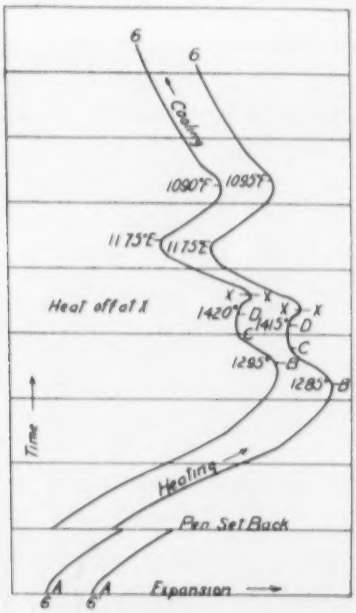


Fig. 2—Typical Time-Dilatation Graphs and Duplicate Curve on Samples from the Same Bar Showing Agreement of Separate Determinations.

curves in Fig. 2 illustrate the agreement obtained on two samples from the same bar of steel.

Data Obtained

Fig. 3 contains a reproduction of one of the curves obtained on each composition of steel studied. These curves are all traced from original graphs with the initial length to the same base line. The actual lengths at the transformation points as well as the equivalent temperature scale will vary with the different steels due to variations in coefficient of expansion and to the fact that the phenomena occur during widely different temperature ranges. In Table II the average temperatures observed for the principle points on the curves are given, while Table III shows measurements of times and expansion or contraction taken directly from the original charts. The unit used for measuring time and length changes on

the chart is one inch. One inch on the time scale is approximately 15 minutes, and one inch on the expansion scale is approximately 0.013 inch change in length of the specimen. It is, of course, recog-

Table II
Transformation Temperatures

No.	Beginning of Ac, Deg. Fahr.	End of Ac, Deg. Fahr.	Max. Temp. Reached, Deg. Fahr.	Beginning of Ar, Deg. Fahr.	End of Ar, Deg. Fahr.	Temp. Diff. Ac and Ar, Deg. Fahr.
1	1350	1550	....	1425	1270	125
2	1345	1385	1400	1298	1263	87
2	....	....	1600	1285	1260	100
3	1343	1408	....	1230	1193	178
4	1415	1520	....	1338	1295	182
5	1307	1438	1460	1165	1075	273
5	....	....	1650	1120	1065	318
6	1290	1418	....	1175	1093	243
7	1453	1548	1550	1350	1285	198
7	....	....	1750	1320	1308	228
8	1480	1572	1600	1330	1240	242
8	....	....	1800	1235	1150	337

Table III
Principle Constants from Dilatometric Curves

No.	Expansion A to B	Contraction B to D	Contraction Ratio $\frac{BD}{AB}$	Time B to D	Hold Time C to D	Time Ratio $\frac{CD}{BD}$	Contraction D to E	Expansion E to F	Time E to F	Max. Temp. reached, Deg. Fahr.
			Per Cent			Per Cent				
1	5.25	0.50	9.5	1.64	0.20	12.2	0.44	0.46	0.63	....
2	5.14	0.30	5.8	0.52	0.10	19.2	0.39	0.22	0.42	1400
2	....	....	..	....	....	....	0.40	0.20	0.49	1600
3	5.24	0.46	8.8	0.58	0.15	25.9	0.84	0.47	0.66	....
4	5.33	0.58	10.9	0.95	0.36	38.0	0.71	0.73	0.51	....
5	4.71	0.84	17.8	1.07	0.35	32.7	1.38	1.13	1.02	1460
5	....	....	....	....	....	....	1.53	1.08	1.19	1650
6	4.73	0.69	14.6	0.80	0.27	33.8	1.18	0.96	0.93	....
7	4.90	0.51	10.4	0.86	0.40	46.5	0.62	0.60	0.52	1550
7	....	....	....	....	....	....	0.72	0.62	0.48	1750
8	4.90	0.88	18.0	0.85	0.25	29.4	0.98	0.97	0.62	1600
8	....	....	....	....	....	....	1.52	1.00	0.76	1800

nized that the values given in Table III would be quite different for other heating rates but since all were obtained on the same uniform basis, it is believed that they are mutually comparable.

An inspection of Fig. 3 will at once disclose that the curves are quite different for the different steels. Steel No. 1, a plain low carbon steel, shows an intermediate transformation on both contracting through the Ac range and expanding in the Ar range. These are probably the Ac_2 and Ar_2 points or the change to and from beta iron. It is interesting to note the large volume changes

on a steel of this low carbon content, although the method is sensitive enough to detect transformation in steels of much lower carbon content. Steel No. 2 shows a much smaller time in the transformation range, lower temperatures, and is typical of water-hardening steels of one per cent carbon. No. 3, is a nondeforming oil-

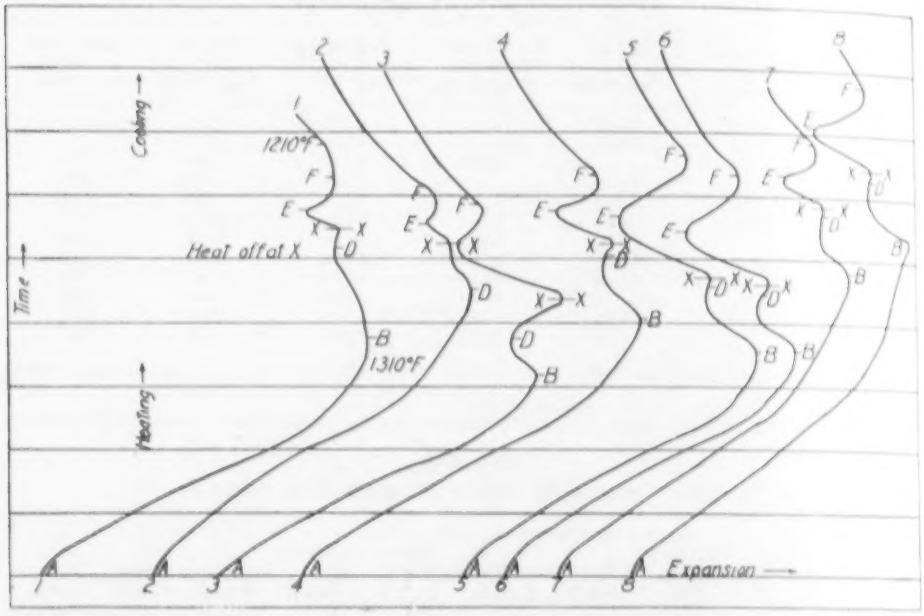


Fig. 3—Time-Dilatation Curves on All Steels Carried to Maximum Temperature Just Above the Ac Point.

hardening type and compared with No. 2 shows the greater volume changes in the transformation range as well as the greater temperature difference between Ac and Ar characteristic of this type.

In the other steels the effect of nickel and chromium is interesting. Nickel depresses the Ac temperatures whereas chromium raises them. Where both are present the effect is intermediate. Nickel also suppresses the Ar temperatures but these are less effected by chromium. The difference between the Ac and Ar temperatures is greatest for the nickel steels reaching nearly 280 degrees Fahr. in the case of steel No. 5. The high chromium steels 7 and 8 also show a large temperature difference but not as great as those containing a less amount of nickel.

Thermal Hysteresis

The authors have found it possible in many cases to quench nondeforming steels from above the Ar point into water instead of oil as is generally necessary and thus secure greater hardness and

still be free from tendencies to crack or change dimensions. The basis of this type of heat treatment is the large thermal hysteresis which exists between the Ac and Ar points in certain steels, particularly those containing nickel and chromium. The dilatometric

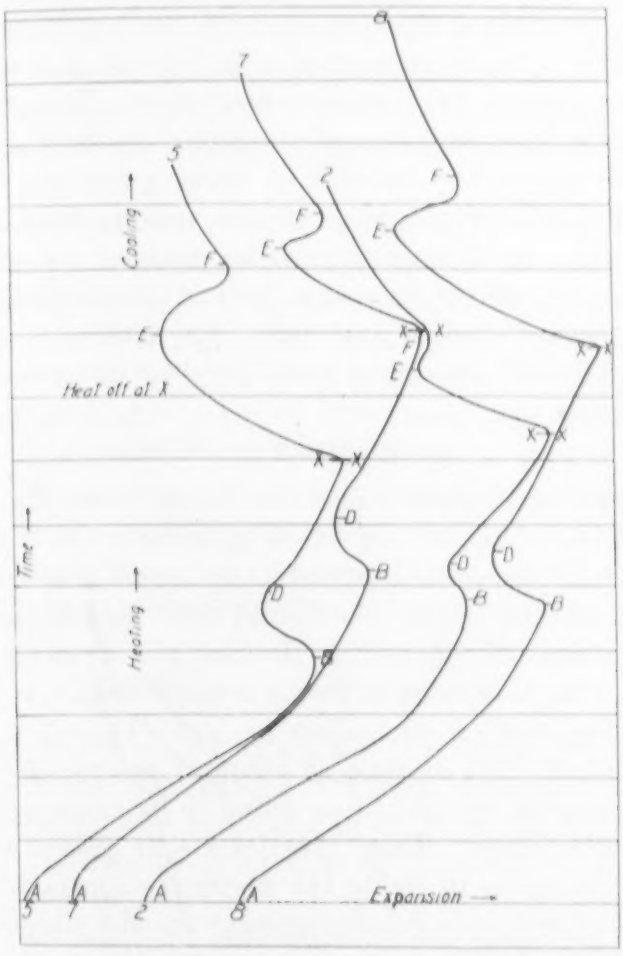


Fig. 4—Time-Dilatation Curves on Steels, 2, 5, 7 and 8 Carried to a Maximum Temperature 200 degrees Fahr. Above the Ac Point.

curves of such steels show that a much smaller volume change has to be taken care of during a quenching from above the Ar point. It is natural to expect that fewer strains will be retained.

By certain means the hysteresis may be increased and the Ar point still further suppressed. One method is to heat considerably above the Ac point, before cooling to the Ar point. In Fig. 4 steels 2, 5, 7 and 8 have been heated about 200 degrees Fahr. above the Ac point before cooling and Tables II and III show the constants

for these curves. For the plain carbon steel the effect on the Ar point has been slight but with increasing chromium content the additional suppression is quite marked, amounting to about 100 degrees Fahr. for the stainless steel No. 8. The time to consummate the Ar transformation is in general somewhat increased.

In a recent paper Egeberg[1] describes the results of experiments in quenching certain chromium-nickel steels just above the Ar point after having previously heated them above the Ac range and intimates that commercial use is not made of this treatment in order to secure the benefits of lower quenching temperatures such as freedom from warping, strains and cracking. The authors are aware of several concerns who are making use of this type of treatment, particularly on shapes having thin sections, in order to secure the higher quality predicted. The method is also fully described by Giolitti[2] who gives results of heat treatments conducted in this manner.

Classification of Steels

In Table III certain constants taken from the dilatometric heating curves of the several steels have been listed and also two ratios derived from these constants. In commercial heat treatment using a dilatometer it has been found the "contraction ratio", defined as the ratio of contraction through the Ac range to the total expansion to the beginning of the Ac transformation, is much greater for truly oil-quenching steels than for water-hardening steels. The "time ratio" or ratio of time at constant volume to total time of Ac transformation has also been noted to be much greater for oil-hardening alloy steels. These theories are in general substantiated by the results shown in Table III where the contraction ratio and time ratio are both considerably greater for the oil-hardening than for the water-hardening steels.

It is suggested that with a further study of a larger number of steels that a rational basis can be formulated for classifying steels into water and oil-hardening in terms of the dilatometric constants. Possibly in determining the limits of such a classification consideration will also have to be given to the cooling curve constants and the effects of higher temperatures in suppressing the Ar transformation.

[1] A Neglected Phenomena in Heat Treatment—Birger Egeberg, Transactions, American Society for Steel Treating, July, 1927, p. 46.

[2] Heat Treatment of Soft and Medium Steels—F. Giolitti. McGraw-Hill Book Co. 1921

Steel manufacturers now recommend oil hardening for many types of steel which it is believed can be treated by water quenching and which a proper study of the dilatometric constants will justify. In commercial heat treatment of dies and tools of unknown composition a decision must be made regarding the proper quenching medium and the suggested classification makes this readily possible. In our own laboratory we have repeatedly made such decisions from our experience in interpreting the charts during the course of heat treatment and the results obtained have justified the decision in all cases.

It is the usual practice in heat treatment by means of the dilatometer to quench the articles being treated at the second reversal in the expansion curve, i. e., at the point where the re-expansion denotes the Ac transformation completed. Naturally pieces quenched previous to the completion of the transformation will not be fully hardened and will be prone to crack, while steel quenched from higher temperatures will be hardened to greater depth but at a sacrifice of structure. The latter condition is, however, essential for some classes of work particularly in heat treating striking dies. The following data was obtained to show the effect of quenching at various definite points on the dilatation curve.

Macro and Microstructure

For the purpose of studying the microstructure the one-per cent carbon steel No. 2 in Table I was used. This steel was selected as it would show greater variations in depth of hardening than the alloy steels. The specimens used were, as shown in Fig. 5, cylindrical bars 1 inch in diameter by 6 inches long cut from machined bar stock. Two saw cuts were made in the specimen to facilitate breaking out the small specimen for examination, but these saw cuts were plugged with brass during the heating and quenching operations.

The left hand curve of Fig. 6 is a composite dilatometric heating curve of the various samples and shows the various stages in the heating at which they were removed and quenched in brine. All were placed in the furnace which was held constant at 1100 degree Fahr. until they were equalized with the furnace temperature as indicated by the vertical line of no volume change. The current was then increased to the maximum rate of heating, the

same as previously described. The specimens were removed at the points on the curve denoted by the letters. B is at the point of contraction or entrance into the Ac range; C is half-way through the transformation and D at the completion of the transformation or

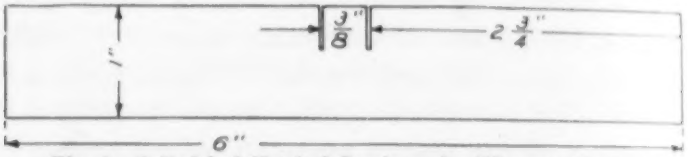


Fig. 5—Cylindrical Notched Specimen for Micrographic Samples Steel No. 2.

the point of re-expansion. E is at the point of 50 per cent recovery of expansion; F at 100 per cent recovery, i. e., where the steel is at the same volume at point B and G at 150 per cent re-expansion.

The dotted line shows the curve for specimen H for which the furnace current was turned off at D, and cooling at the natural furnace rate takes place up to point H which is 20 degrees Fahr.

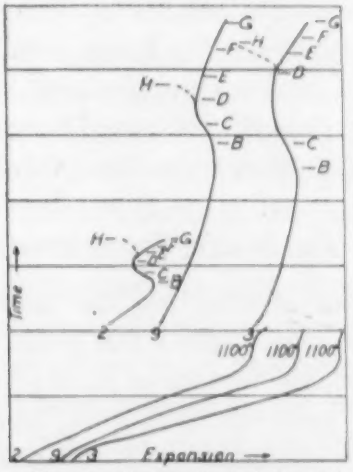


Fig. 6—Composite Dilatometric Heating Curves of Steels Nos. 2, 3 and 9 used for Microscopic Examination and Distortion Tests.

higher than the beginning of the Ar transformation as previously determined. The sample was then brine-quenched similar to the others. All of the points on the curves were readily obtained by means of the automatic signals and the dial indicator. The corresponding temperatures are shown in Table IV.

The Rockwell "C" hardness was obtained on all the specimens which were then broken through the notches. Table V shows the hardness values and depth of hardening as estimated by a scale on the fractured section. All hardness values reported are the aver-

age of about ten readings. Specimen A in Table V is the original material not heat treated.

The photomicrographs in Fig. 7 are taken on cross sections of the specimens directly at the hardened edge with the exception of

Table IV
Temperatures Corresponding to Points in Figure 6

Speciman No.	Steel No. 2	Steel No. 9	Steel No. 3
B	1345	1345	1340
C	1370	1370	1360
D	1385	1385	1410
E	1425	1420	1445
F	1455	1450	1460
G	1480	1485	1480
H	1320	1270	1250

A which is the normal structure in the center of the material. The magnification is so chosen as to include all the hardened sections and a portion of the underlying core.

In Fig. 8 the various photomicrographs show the structure at the junction of the hardened and non-hardened portions of the cross

Table V
Hardness and Depth of Hardening of Specimens Shown in Figure 7. One Per Cent Carbon Steel No. 2

Specimen No.	Hardness Rockwell "C" Scale	Depth of Hardening Inches
A	4	None
B	30	None
C	58	0.02
D	63	0.09
E	64	0.09
F	64	0.11
G	64	0.11
H	65	0.09

sections at a magnification of 100x. The top of the photograph in all cases is nearest the hardened edge.

From these data it can be seen that B has just started to harden and that the grain size is much larger than the untreated material A. Specimen C is of still larger grain size, has a slight depth of hardness and an appreciable surface hardness. D has the desired fine grain, considerable depth and full hardness. Sample E is quite similar to D but with one point greater hardness. The depth of hardening is greater in both F and G but with considerable en-

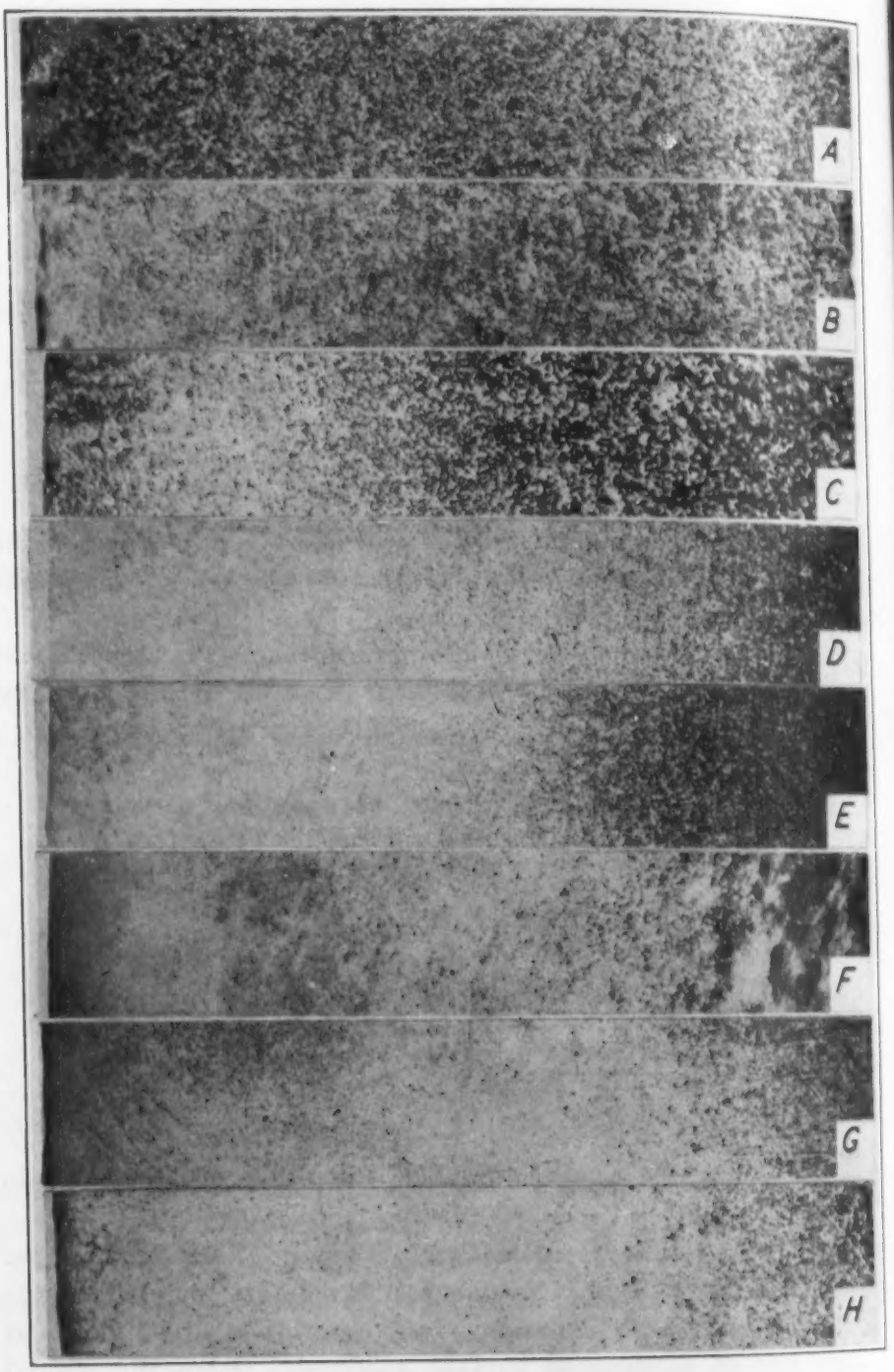


Fig. 7—Photomicrographs of the Edge of Cross Sections of Steel No. 2. Mag. 30x. Specimens Etched with Picric and Hydrochloric Acids in Alcohol.

largement of grain size. H, which was treated to take advantage of thermal hysteresis, is quite interesting, having the maximum hardness of all specimens, good depth and fine grain. As will be shown later this treatment also brings about the least warpage and size changes.

Distortion Tests

For the purpose of studying the effect of the various quenching points on warping, a typical water-hardening and a typical oil-hardening nondeforming steel was used. These were steels No. 9 and 3 respectively. Although steels No. 9 and No. 2 are the same brand and practically identical in composition, they are from separate bars of stock and showed some variance in dilatometric constants and behavior in subsequent heat treatment.

A sketch of the specimen used in these tests is shown in Fig. 9. This is a cylindrical specimen 1 inch in diameter for half the length and ½ inch diameter for the remainder. As sharp a corner as possible was machined between the two sections. Two holes were also drilled as indicated. The stepped shoulder was for the purpose of measuring the eccentricity by means of a dial gage when rotated on the centers both before and after heat treatment.

It was anticipated that this specimen with its several variations in cross section, some of which were quite thin, and the sharp corner would develop cracks especially under some of the conditions of heat treatment. However, in only one case were cracks observed.

The specimens were heated in much the same manner as the specimens for microscopic examination; the heating curves are included in Fig. 6 where the letter designations are the same as before. After the equalization at 1100 degrees Fahr. the heating rate was much slower being about one third as rapid as that used previously. One complete set of the No. 9 steel (one per cent carbon) was quenched in brine (Fig. 10). For the oil-hardening steel two sets were run, one of which was quenched in brine and the other in oil. Temperatures corresponding to the quenching points are given in Table IV.

Eccentricity or warping measurements were taken on all the specimens. The diameters on both large and small sections of the No. 3 steel specimens were measured before and after treatment. The results of all these measurements as well as the hardness tests are given in Tables VI, VII, and VIII.

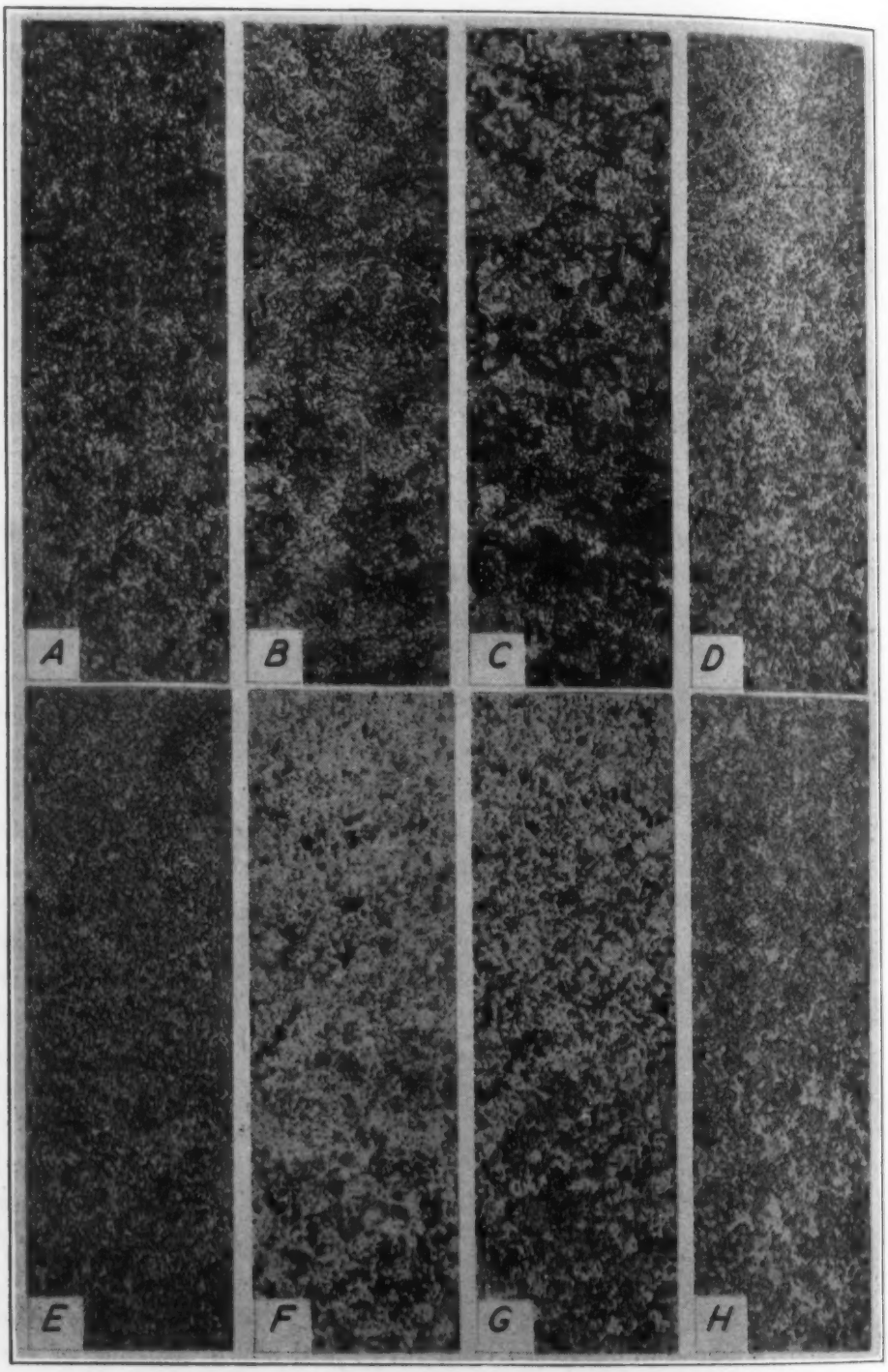


Fig. 8—Photomicrographs of the Junction of the Hard and Non-Hard Portions of Steel No. 2. Mag. 100x. Etched with Picric and Hydrochloric Acids in Alcohol.

Table VI

Hardness and Eccentricity of Steel No. 9—Brine-Quenched

Specimen No.	Hardness Rockwell "C" Scale on Small Diameter	Eccentricity Inches	Fracture
B	20	0	No break
C	51	0.0015	Tough
D	65	0.005	Tough
E	65	0.0055	Brittle
F	64	0.006	Brittle
G	64	0.007	Brittle
H	63	0.0005	Brittle

Table VII

Hardness and Eccentricity of Steel No. 3—Brine-Quenched

Specimen No.	Hardness Rockwell "C" Scale on Small Diameter	Eccentricity Inches	Increase in Diameter Inches		Fracture
			Large End	Small End	
B	24	0.0005	0	0	No Break
C	51	0.004	0.001	0.0005	Tough Coarse
D	65	0.0055	0.0015	0.001	Brittle Fine Grain
E	65	0.003	0.0015	0.0015	Brittle Coarse
F	64	0.004	0.0015	0.0015	Brittle Coarse
G	64	0.008	0.0015	0.002	Brittle Coarse
H	64	0	0.0015	0.0005	Tough Fine

Table VIII

Hardness and Eccentricity of Steel No. 3—Oil-Quenched

Specimen No.	Hardness Rockwell "C" Scale on Small Diameter	Eccentricity Inches	Increase in Diameter Inches		Fracture
			Large End	Small End	
C	33	0.0005	0	0	No Break
B	12	0.0015	0	0	Tough Coarse
D	62	0.0025	0.0005	0.001	Tough Fine
E	61	0.003	0.0015	0.001	Brittle Coarse
F	61	0.004	0.0015	0.001	Brittle Coarse
G	59	0.010	0.0015	0.0005	Brittle Coarse
H	63	0.002	0.001	0.0005	Tough Fine

After the measurements were made the specimens were broken. All specimens which are noted as brittle in the tables broke in the sharp shoulder with a slight tap, the tough specimens required several heavy blows to break and in general broke through the

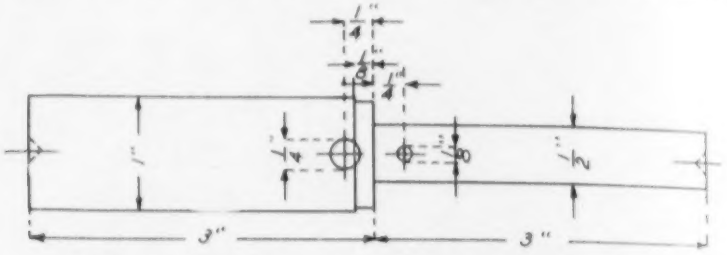


Fig. 9—Cylindrical Specimen for Distorsion Tests. Steels No. 3 and 9.

small hole away from the shoulder. The only specimen in which a quenching crack was discovered was in the G specimen of Steel No. 9 which had a fine crack emanating from the large hole.

In all of these samples the smaller sections have hardened completely through or have a uniform hardness on a cross section. For the No. 9 steel specimen D is structurally the best having maximum

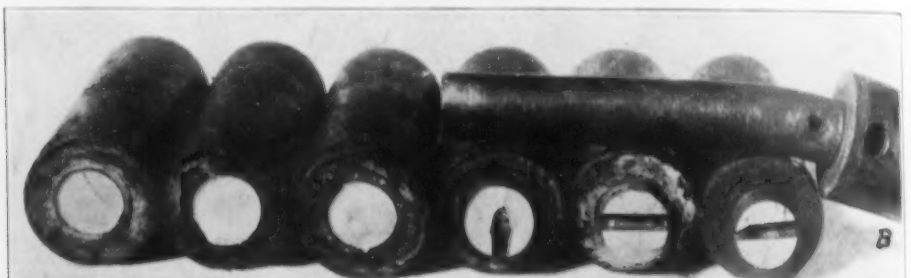


Fig. 10—Fractured Distorsion Specimens Steel No. 9. Brine Quenched.

hardness, toughness and minimum of warping. The results on the No. 3 steel are quite interesting and show that under certain conditions this type of steel may be safely quenched in water or brine and greater hardness secured but with greater dimensional changes and distortion. In the brine-quenched series specimen H shows greater hardness than any of the oil-quenched series together with smaller dimensional changes and lack of distortion. This substantiates the statement previously made that oil-hardening steels when treated to take advantage of thermal hysteresis can be safely

water-quenched and with superior results. In the oil-quenched series treatments D and H appear the best from all standpoints.

Comparison of steels Nos. 9 and 2 brings out interesting results. Although these two steels are for practical purposes identical in composition of the usual elements determined, the dilatometric constants are different. No. 9 shows much less contraction in the Ac range and the Ar temperatures are lower. No. 9 hardened much deeper than No. 2 which was shown by further tests not reported here. It is possible that dilatometric analysis furnishes a means of foretelling which steels will harden the deepest.

Summary

1. Dilatometric curves of some commercial steels have been obtained and from these curves certain fundamental dilatometric constants and transformation temperatures obtained.

2. From these dilatometric constants it is proposed to classify steels according to their proper quenching medium although further study is necessary to set the limits for such a classification.

3. Heat treatment taking advantage of thermal hysteresis is discussed and a means shown for further increasing hysteresis and securing the benefits of still lower quenching temperatures for certain steels.

4. Normal oil-quenching steels when treated to take advantage of thermal hysteresis may be brine-quenched with superior results.

5. As a result of all the tests it appears that heat treatment D, quenching at the completion of the transformation or point of re-expansion, produces the best properties. The quenching point for this treatment can be readily obtained by the automatic signal device on the dilatometer.

6. When greater depth of hardness is essential other fixed points on the dilatometric curve may be used at the sacrifice of toughness and grain size.

DISCUSSION

H. J. French: I would like to ask Mr. Woodward to say a few more words regarding the significance of what he has called his time factor. I was not able to follow the numerical values at the time the slides were shown, but I would like to have him tell us the significance of that time factor in relation to the practical treatment of the steels which he has considered.

R. W. WOODWARD: It is a new idea that we are endeavoring to develop, in the hope that we will be able to definitely classify an unknown steel, for instance, into either an oil-hardening or water-hardening classification. The various constants which were shown quite well fall into such a general classification. Of course, there are plenty of steels which have an intermediate classification, but by studying a great number of steels, which we hope to do, and I believe other people are also doing, we hope it will eventually be possible to definitely say whether a given steel should be water-quenched or oil-quenched in order to give the best physical properties consistent with size changes or other properties which also have to be considered.

E. P. STENGER: Mr. Chairman, I would like to ask Mr. Woodward how high above the Ac_3 point he carried the expansion, that is, at about what point above re-expansion was the temperature carried before it was again allowed to drop to the Ar_3 point?

R. W. WOODWARD: Ordinarily, they were not carried any farther. As soon as the automatic signal indicated that the steel had passed completely through the Ac transformation, the furnace current was turned off and the specimen allowed to cool until it was 20 degrees above the beginning of the previously determined Ar temperature. Of course, that point, as I mentioned in the first part, could have been further lowered in a good many of the steels by carrying re-expansion to a higher temperature.

C. T. PATTERSON: I would like to ask Mr. Woodward how much difference in temperature there was between the outside of the specimen after he turned off the heat and the inside where the pyrometer was when it reached the point H.

R. W. WOODWARD: That point was not definitely determined. I have one of the specimens here if you would like to examine it later, and I think you could see for yourself that a specimen of that size will probably have a fairly small temperature gradient throughout its cross-section in a slow cooling medium.

H. C. KNERR: Mr. Chairman, it may be a little aside from the subject of the paper, but I would like to ask Mr. Woodward if the dilatometer has been adapted for following the changes during quenching.

R. W. WOODWARD: We have not ourselves carried out any such experiments, but I believe it could be arranged, though it would present quite a few experimental difficulties in carrying it out.

E. P. STENGER: In regard to applying the dilatometer to the quenching of steels, I think if it could be worked out, it would be very fine and would eliminate a great deal of the breakage in tool hardening, especially on water-hardening steels. It is very common practice in quenching water-hardening steels to depend on the hardener bringing the tool out of the water and finishing the quench in oil at a certain point which is more or less roughly determined by the vibration leaving the tongs. If the dilatometer could be made to take care of that, I think it would be a very big help to the heat treater. I have tried experiments along this line, but, as Mr. Woodward pointed out, the practical application of the dilatometer to this purpose is very difficult.

ON THE SIGNIFICANCE OF THE PROPORTIONAL LIMIT OF STEEL AT ELEVATED TEMPERATURES

By Francis B. Foley

Abstract

A considerable amount of research is being carried on to determine the physical properties of steel at elevated temperatures. The testing of metal at elevated temperatures presents problems not encountered at atmospheric temperatures.

The most valuable and most difficult value to determine is the true elastic limit. The author suggests the possibility of developing a mathematical expression of the relationship of the proportional limit determined at elevated temperatures to that obtained at room temperature and gives evidence from available data of a straight line relationship between the temperature of testing and the sum of two factors; namely, the strain produced at the proportional limit and the thermal expansion at the temperature of testing.

INTEREST in the strength and reliability of steel at elevated temperatures has of recent years led to a considerable amount of research. The problems met with in the design of equipment for use at elevated temperatures are, however, so numerous as to provide subject matter for investigations that will, no doubt, cover many years. As with most developments the practical application will go forth to lead the way and laboratory research, gleaning considerable from industrial experiences, will supply the refinements which ultimately will lead to the goal of lighter and stronger construction.

The testing of metal at elevated temperatures presents difficulties not present, or present to an inconsequential degree, in similar operations at atmospheric temperatures. Every difficulty encountered in ordinary tensile testing is exaggerated as the temperature of the specimen under test is increased. For metal which is to be subjected to mechanical stresses at normal tem-

A paper presented before the ninth annual convention of the society held in Detroit, September 19 to 23, 1927. The author, F. B. Foley, a member of the society, is superintendent of research of the Midvale Company, Nicetown, Philadelphia. Manuscript received July 18, 1927.

peratures the ordinary tensile test supplies some data useful in designing equipment, but such tests frequently have to be supplemented by other tests for shock resistance, wear and soundness. Tensile testing at elevated temperatures is only the beginning perhaps—yet a very great amount of useful information concerning the behavior of steel under the influence of heat is being derived from such work.

Undoubtedly the most difficult value to determine, in any circumstance, is the true elastic limit of steel and unfortunately it is also the most valuable bit of information determined in tensile testing. Ordinary tensile tests give values representing tensile strength, elastic limit, extension and contraction of area. The tensile strength is the breaking load expressed in load per unit of area; the extension represents the amount a measured length has stretched during the test, given in per cent; and the contraction is the amount the specimen necks down during the test given in per cent of the original cross sectional area. The elastic limit is commonly determined by measuring the amount a measured length of specimen stretches for even increments of added load and thus determining the load at which a uniform increase in the measured length produced by the even increments of added load ceases. The value which it is supposed to represent is the maximum load upon the removal of which there is no permanent increase in the original measured length of the test piece. It is doubtful if it can be said that the elastic limit obtained is never that true value, but it is safe to say that it seldom is and this refers particularly to the ordinary test at atmospheric temperature. How near the result obtained approximates a true elastic limit depends on the accuracy with which the readings of extension during the test are made. The various methods of determining the elastic limit give rise to a variety of names, so that, beside "elastic limit", we have "proportional limit", "Johnson elastic limit" and "yield point".

Elastic limit has come to mean an elastic limit determined by means of some type of extensometer, usually equipped with a dial, and with which readings are taken with an accuracy of 0.0001 inches at each increase of 1000 pounds load on the specimen. A more delicate type of extensometer may be used, the readings plotted, and the point at which the extension ceases to

be proportional to the load is located and designated as the "proportional limit". In determining the *Johnson elastic limit* a stress-strain diagram is used and the point determined by construction following an arbitrarily established method. *Yield point* may be determined by either the extensometer or by noting the load at which the beam of the testing machine drops. Sometimes this is well marked and at other times it is difficult to identify. There is a time factor involved in this latter method. Once the elastic limit has been reached the load may be kept on the specimen and if enough time is allowed the beam will sooner or later drop. Here in ordinary testing at atmospheric temperature we have the phenomenon of "flow" met with in a more exaggerated form in testing steel at elevated temperatures—which might have been expected since the plasticity of metal increases as its temperature increases.

The first efforts to determine the physical properties of steel under the influence of heat consisted of heating the specimen, maintaining its temperature at the desired point and pulling it apart precisely as metal had been tested at atmospheric temperature. French and McVetty, two men prominently identified with elevated temperature testing, have found that elastic limits determined at elevated temperatures in the ordinary manner are about as true as a "drop of beam" determination at atmospheric temperature. Heated specimens under tension of loads short of their elastic limit, as determined in the ordinary fashion, continued to stretch and ultimately failed—at times in hours and sometimes in months (conceivably it might be years), depending on how near the load applied was to the true elastic limit. In other words, the metal continued to "flow" without increase of load when stressed above its true elastic limit. This phenomenon also exists with ductile metals at atmospheric temperature and the designing engineer's answer to it is the application of a large safety factor in his construction. There are, however, types of construction, in which the weight cannot be arbitrarily increased and where lightness is imperative, which will frequently be necessary in designing equipment for use at high temperatures. There will therefore be occasions where ordinary high temperature elastic limits will furnish data of sufficient accuracy and others where determinations of the greatest precision will be necessary,

just as in atmospheric temperature work,—the yield point gives accurate enough data for certain purposes whereas an accurately determined elastic limit is essential in other instances.

There are types of steels which, in atmospheric testing, produce a stress-strain relationship which does not appear linear at all and instances of this kind also appear in elevated temperature testing. In discussion[1] French suggests that with sufficiently sensitive measuring devices it might be developed that a zero rate of creep existed only under zero load. This reference is made in connection with elevated temperature testing and is put forth by H. J. French only as an academic consideration, probably mainly to emphasize the point that, with steel under the influence of heat, the time factor must be considered in connection with load. The long time elevated temperature tests he has made have led him to emphasize the influence of time under load and have given rise to the terms "maximum stress for long life with deformation" and "maximum stress for long life without appreciable deformation". What is "long life" and what is "appreciable deformation"? These are not precise terms, but precision for one working in terms of thousandths of an inch is not precision for one handling millionths of an inch. As French has already stated there are constructions which will permit of a certain amount of deformation, others that will permit of much less. This leads again to the consideration that for some purposes the ordinary elastic limit determination will give satisfactory data and that for others a more precise determination is necessary.

It will be some time before we shall be able to determine the most satisfactory compositions for use at elevated temperatures. This thought is prompted by a consideration of the variables involved. In order to obtain values for a given steel we foresee the necessity of testing it at various high temperatures after it has been put in certain initial metallographic conditions. It may for example be prepared by simple normalizing, by annealing, by annealing and tempering, and by quenching and tempering. It has always been maintained that the physical properties of a quenched steel undergo change with time of exposure to a constant tempering temperature. We are inclined to believe that the effect of time in tempering is greater on a quenched

[1] TRANSACTIONS, American Society for Steel Treating, Vol. XI, No. 1, Stainless Iron at High Temperature, McVetty and Mochel.

steel than on one that has been slowly cooled from above its critical temperature previous to its reheating to temperatures below its critical range. We should therefore not be inclined to depend too greatly on the stability of properties, determined at elevated temperatures, of steel which was initially in the quenched state. In work so far published it is evident that the results obtained at elevated temperatures do depend a great deal on the initial state of the metal tested. On the other hand, steel which has been hardened and tempered is possessed of physical properties which are not altered materially by any subsequent reheating to temperatures below the temperature of tempering.

Certain high temperature equipment is not maintained continuously throughout its life at an elevated temperature, but undergoes heating and cooling. Such service may present an entirely different subject for consideration from that in which there is continuous exposure to the high temperature.

Most of us are acquainted with the phenomenon of increased elastic limit produced by subjecting steel to repeated stressing under loads somewhat greater than the elastic limit. This phenomenon is found to exist apparently only in the strain-hardening range of temperature. It is produced by stressing and then removing the load. The other matter for investigation is the stressing at elevated temperature under load exceeding the elastic limit and then removing the load, cooling to atmospheric temperature, reheating and again applying the load. Conceivably with the release of the load there may be a healing during the cooling down in the nature of a relieving of strain similar to that produced in tempering operations. It is even conceivable that there may be a sort of healing going on even during the progress of the test.

In testing at atmospheric temperature there is a measurable amount of stretch which is observed throughout the test in determining the elastic limit. Under loads up to the proportional limit the strain is probably uniform throughout the measured length of the specimen. This strain may be conceived, within the limit of proportionality, as a separating of the atom layers. Upon the releasing of the load the atoms find their original position relative to their neighbors. When the limit of proportionality has just been exceeded the separation exceeded that in which

restoration is possible. The proportional limit would then establish a limiting spacing beyond which restoration does not take place upon removal of the load. In elevated temperature testing this limit is attained as the sum of two factors. A portion of the spacing is produced by thermal expansion and the remainder is the result of mechanical stressing. If this spacing were

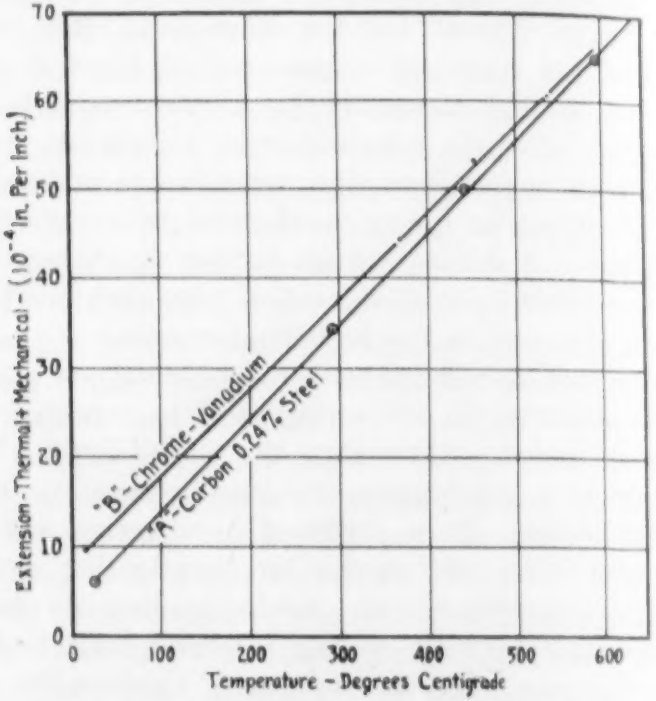


Fig. 1—Total Extension at Limit of Proportionality.

a constant the sum of the linear expansion per unit gage length due to heating to a given temperature and the total strain per unit length produced at the limit of proportionality during stressing at that temperature would equal the total extension found at the limit of proportionality in testing the same material at room temperature. This would be true as long as the crystalline arrangement remained unchanged which, in steel, would be the case up to the allotropic change point. There are insufficient data at hand to show whether this has any foundation in fact.

A series of stress-strain curves obtained by McVetty[2] on a carbon steel having a carbon content of 0.24 per cent tested at 80, 563, 833 and 1103 degrees Fahr. (27, 295, 445 and 595 de-

[2] *Proceedings*, American Society for Testing Materials, 1926, Vol. 26, Part 2, page 18.

grees Cent.) show the amount of strain, measured with a precision extensometer, at the proportional limit in each case. Using these figures and a mean coefficient of linear expansion of 11×10^{-6} per degree Cent. we obtain the figures in Table I:

Table I

Expansion of a Carbon Steel Having a Carbon Content of 0.24 Per Cent

°C.	°F.	Strain In. per Inch	Thermal Expansion In. per Inch	Total Mechanical plus Thermal Extension In. per Inch
27	81	0.0006	.....	0.0006
295	560	0.000475	0.002948	0.003423
445	830	0.0004	0.004598	0.004998
595	1100	0.000225	0.006248	0.006473

It is apparent from Table I that the spacing is not a constant. Fig. 1, Curve A, shows how the total extension at the proportional limit increases with increase in temperature. This same phenomenon holds good for a steel having a content of carbon of 0.34 per cent, chromium 2.36 per cent, vanadium 0.20 per cent, tested by French, from which values were obtained for Table II, and for the construction of Curve B, Fig. 1.

Table II

Expansion of an Alloy Steel at Elevated Temperatures

Carbon 0.34%; Chromium 2.36%; Vanadium 0.20%

°C.	°F.	Strain In. per Inch	Thermal Expansion In. per Inch	Total Mechanical plus Thermal Extension In. per Inch
18	64	0.00097	.....	0.00097
370	700	0.00055	0.003872	0.004422
455	850	0.0005	0.004807	0.005307
540	1005	0.00032	0.005742	0.006062

Using the actual increase with temperature in the *a* parameter of the fundamental cubic unit of iron obtained by X-ray spectrometry by Westgren and Phragmen[3] as the spacing between atoms and calculating from stress-strain diagrams the increase

[3]Westgren and Phragmen, *Journal*, Iron and Steel Institute, 1922.

produced by mechanical stress the same data can be obtained for the fundamental cube unit showing the actual increase spacing at the proportional limit for various elevated temperatures as in Tables III and IV and Fig. 2.

Table III

Expansion of a Carbon Steel at Elevated Temperatures

Carbon 0.24%

°C.	°F.	Mechanical Expansion of *a* Parameter 10^{-13} cm.	Thermal Expansion of *a* Parameter 10^{-12} cm.	Mechanical Plus Thermal Expansion 10^{-13} cm.
27	81	17.2	...	17.2
295	560	13.6	100	113.6
445	830	11.4	150	161.4
595	1100	6.4	215	221.4

Table IV

Expansion of an Alloy Steel at Elevated Temperatures

Chromium-Vanadium Steel

°C.	°F.	Mechanical Expansion of *a* Parameter 10^{-13} cm.	Thermal Expansion of *a* Parameter 10^{-12} cm.	Mechanical Plus Thermal Expansion 10^{-13} cm.
18	64	27.8	...	27.8
370	700	15.8	120	135.8
455	850	14.3	160	174.3
540	1005	9.2	190	199.2

Evidently, as temperature increases, it is possible to greatly increase the distance between atom centers without producing permanent deformation. Atoms are conceived of as having a cohesive power—they are held to each other in a solid at normal temperatures. Under the influence of heat the spacing increases. Upon the application of sufficient heat the solid changes to liquid and finally disintegrates as a gas. This increase of spacing is caused by a movement of the atom as a system and also perhaps by an increase of motion within the individual atomic systems;

the movement of the entire atom system being about a center and the change of motion an increase in the speed of revolution of the planetary electrons about the nucleus. Either of these

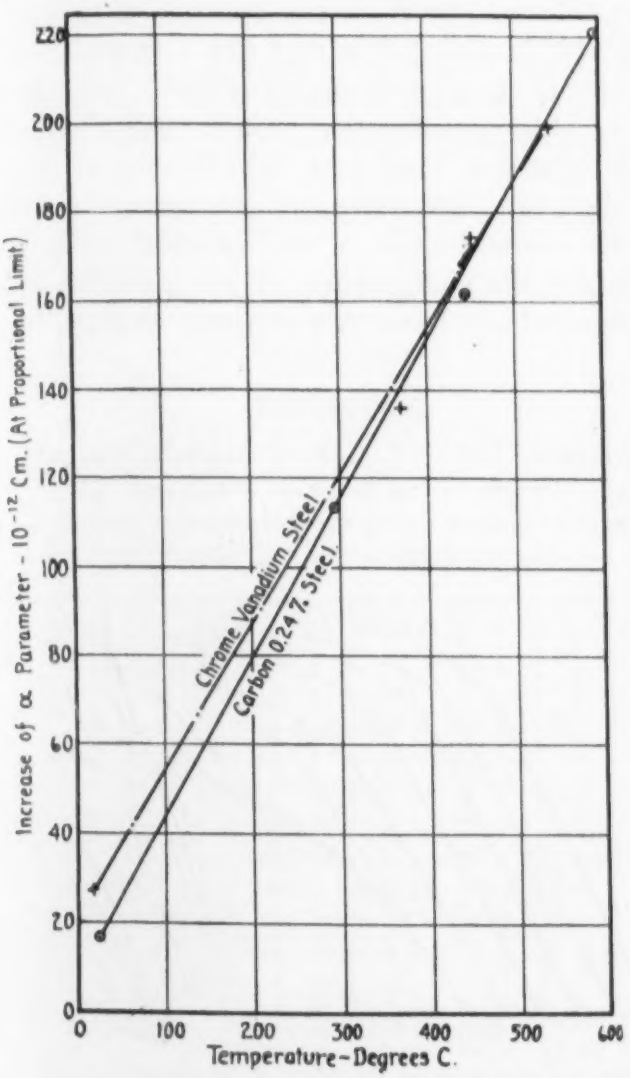


Fig. 2—Increase in a Parameter of Fundamental Unit with Temperature.

changes with temperature would bring about an increase in the sphere of influence about each center; in one case the atom moves in a larger field and in the other the energy is increased. By virtue of this kinetic motion the power of restoration or healing is increased. Optically flat surfaces of steel in contact, heated in vacuum, weld perfectly without mechanical pressure.

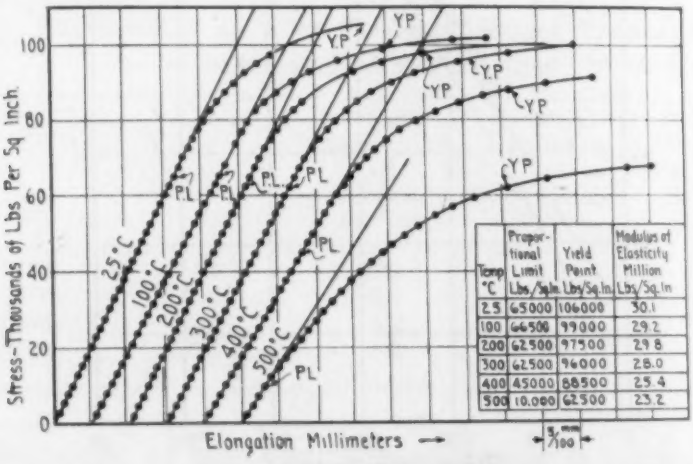
While the maximum spacing of its atom centers which a steel is able to withstand without permanent displacement increases with temperature, the stress which is required to produce spacing decreases. This is evident from the decrease of modulus of elasticity from 29×10^6 in the carbon 0.24 per cent steel at room temperature to about 18×10^6 at 1100 degrees Fahr. (595 degrees Cent.).

It appears quite possible that, when certain data are available, such as expansion coefficient, relationship of strain at the proportional limit to temperature and the change of modulus with temperature for various steels, a mathematical analysis will furnish the basis for the computation of the probable elastic limit at elevated temperatures from that obtained at room temperature.

DISCUSSION

Written Discussion: By P. G. McVetty, research department, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

Mr. Foley is to be congratulated upon his careful analysis of the results of tensile tests at elevated temperatures. I regret that I have no experi-



Temp °C	Proportional Limit Lbs./Sq.In.	Yield Point Lbs./Sq.In.	Modulus of Elasticity Million Lbs./Sq.In.
25	65000	106000	30.1
100	66500	99000	29.2
200	62500	97500	29.8
300	62500	96000	28.0
400	45000	88500	25.4
500	10.000	62500	23.2

Fig. 1—Curves Showing the Effect of Temperature on Elastic Properties of Stainless Iron Forged and Heat Treated.

mental data which are applicable, but I should like to consider briefly the high temperature tensile test from which proportional limit values are obtained.

Fig. 1[1] shows stress-strain curves at various temperatures and it is quite evident that the proportional limit value is difficult to determine because it marks the beginning of deviation of the stress-strain curve from the straight

[1]T. D. Lynch, N. L. Mochel, and P. G. McVetty: The Tensile Properties of Metals at High Temperatures. *Proceedings*, American Society for Testing Materials, Vol. 25, Part II, page 10, 1925.

line. As Mr. Foley has mentioned, this determination becomes more difficult as the temperature is increased.

Fig. 2[2] shows how the sensitivity of the extensometer affects the measured values of proportional limit for two different materials tested at 750 degrees Fahr. (400 degrees Cent.). If one-thousandth of an inch is the smallest observable movement of the extensometer, it is evident that 23,000 and 83,000 pounds per square inch would be recorded as the respective proportional limits of these specimens of medium carbon steel and stainless iron.

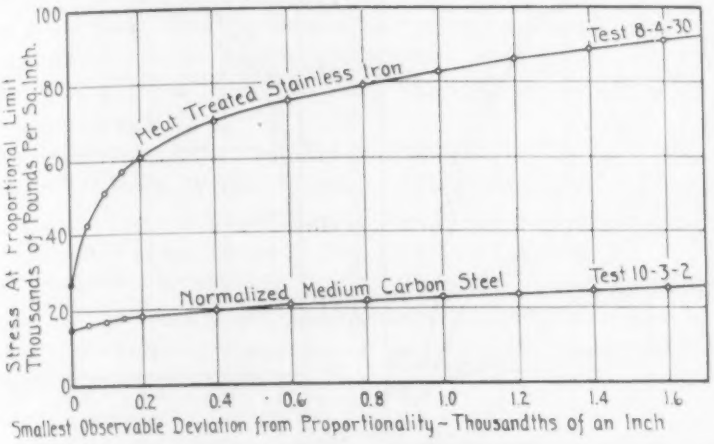


Fig. 2—Curves Showing the Effect of Accuracy of Strain Measurement Upon the Determination of Proportional Limit. From Tensile Tests at 400 degrees Cent.

If four-millionths of an inch is the smallest observable movement, as in the case of the Martens extensometer, the measured values are 15,000 and 27,000 pounds per square inch respectively. If we assume the latter values to be correct, the error of an extensometer reading to 0.001 inch would be about 50 per cent for the medium carbon steel, and about 200 per cent for the stainless iron. This emphasizes the importance of accurate strain measurement at elevated temperatures especially when testing alloy steels.

Fig. 3[3] shows how the proportional limits of several materials vary with temperature. All of these values were obtained with a modified form of Martens extensometer.

Fig. 4[4] shows the results of a long time tensile test in which the elongation is plotted against the time. This type of test supplements the ordinary short time tensile test at elevated temperatures. Even though the stress is 5 per cent lower than the proportional limit, as determined by a Martens extensometer, the test specimen stretched during the first eight hundred

[2] P. G. McVetty and N. L. Mochel: The Tensile Properties of Stainless Iron and other Alloys at Elevated Temperatures. TRANSACTIONS, American Society for Steel Treating, Vol. XI., page 88, 1927.

[3] P. G. McVetty and N. L. Mochel: The Tensile Properties of Stainless Iron and other Alloys at Elevated Temperatures; TRANSACTIONS, American Society for Steel Treating, Vol. XI, page 80, 1927.

[4] P. G. McVetty: Discussion of paper by H. J. French on "Methods of Test in Relation to Flow in Steels at Various Temperatures;" *Proceedings*, American Society for Testing Materials, Vol. 26, Part II, page 30, 1926.

hours of the test and reached a length 26 per cent greater than the elastic deformation for the same stress as measured in the short time test. For design purposes, it is essential that we know the extent of this "creep" under the combined action of stress and temperature. This requires that the test be extended until no further elongation can be detected. For these

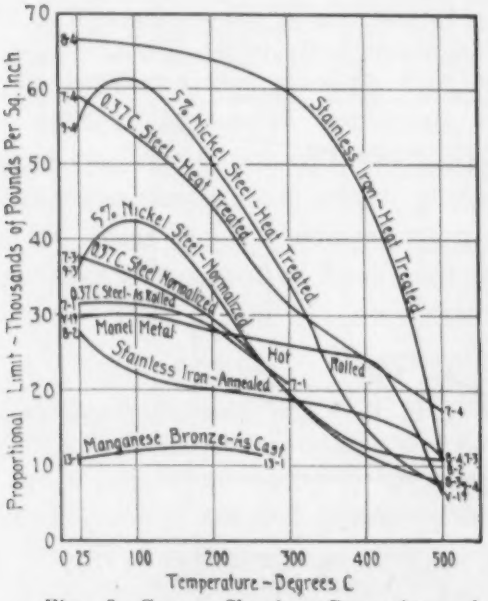

Proportional Limit - Thousands of Pounds Per Sq. Inch
Temperature - Degrees C
0.37C Steel - Heat Treated
5% Nickel Steel - Heat Treated
Stainless Iron - Heat Treated
5% Nickel Steel - Normalized
0.37C Steel Normalized
0.37C Steel - As Rolled
Monel Metal
Stainless Iron - Annealed
Hot Rolled
Manganese Bronze - As Cast

Fig. 3—Curves Showing Comparison of Proportional Limits of Several Materials at Various Temperatures.

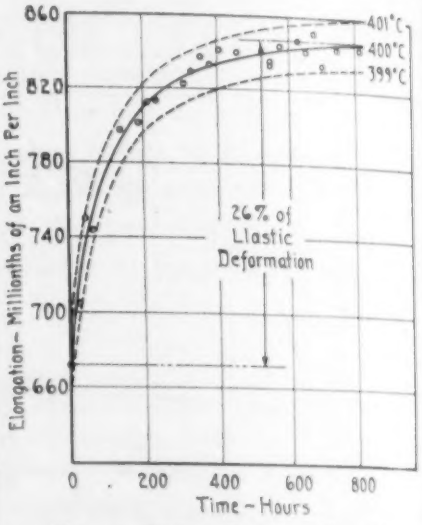


Fig. 4—Curves Showing Flow of Annealed Stainless Iron with Increase of Time. 18,000 Pounds Per Square Inch—400 degrees Cent. (Proportional Limit at 400 degrees Cent.—19,000 Pounds Per Square Inch.)

tests we find it desirable to use a modified Martens extensometer which will detect changes in length of the order of one-millionth of an inch.

As sensitivity of strain measurement increases, the matter of temperature control becomes more and more important. The dotted curves in Fig. 4 indicate the effect of temperature variations of plus or minus one degree Cent. While the observations all fall within this range, it is evident that the test must be continued long enough to make it certain that creep has stopped. A better temperature control becomes absolutely essential if the same information is to be secured in a shorter time.

Design is usually based upon some chosen value of safe working stress, modified by a factor of safety covering the difference between test conditions and service conditions. This factor must also include the difference between the material in the test specimen and the material in the weakest section of the particular application.

In a recent paper[5] before the Institution of Mechanical Engineers, Bailey contends that there is no creep limit. If this is the case, many design applications must be based upon allowable deformation within the life of the material.

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[5]R. W. Bailey—Physical Properties of Metals and the Design of Plant for High Temperature Service. Institution of Mechanical Engineers, Northwestern Branch, 1927.

Mr. Foley bases his argument upon the separation of the atoms as a function of stress and temperature.

I think another theory should be mentioned at this time. The proportional limit may be considered as the beginning of plastic flow. When the proportional limit is exceeded, permanent set results from slipping of the crystals along planes of maximum shear which would be at an angle of about 45 degrees with the direction of the principal stress. Since the material under test usually consists of a crystalline aggregate in which the crystals are oriented in various directions, the beginning of slip probably occurs in the crystal which is most unfavorably situated with respect to the maximum shear stress. In this respect the computation of elastic limit at elevated temperatures from test data obtained at normal temperature may offer some difficulty.

Our experience indicates that fundamental tests will alone reveal the basic facts required by the designer. While mathematical analysis may at times serve to explain experimental results, it is doubtful if such analysis can ever replace properly conducted laboratory tests.

In conclusion it appears that much more research on this subject is necessary. In the meantime, each case must be considered by itself with proper consideration of the type of material, the methods of test and the conditions to be met in service.

Oral Discussion

H. C. KNERR: Mr. Foley's paper takes us rather deeply into the theory of the mechanical properties of metals, and as a consequence into the question of the construction of metals. Any careful analysis into the behavior of metals under stress is bound to do this.

Theory of elastic deformation has heretofore been based on the assumption that metals are homologous, and that stress distribution is perfectly uniform. Actually these assumptions are never strictly true. The small deviations account for most of our difficulties when measurements of high precision are undertaken. Metals ordinarily consist of an aggregate of crystalline particles, arranged in all possible orientations. Each crystal has many planes and directions of potential slip. The properties, including elastic modulus, differ along various atomic planes. Usually more than one phase or constituent is present. Grain boundary metal is imperfectly crystalline, if not truly amorphous, partaking therefore of the nature of an undercooled liquid, or vitreous amorphous material. Such material, if plastic, deforms by flow. Viscosity varies greatly with temperature, so that resistance to permanent deformation may be greater than that of crystalline material at low temperatures, and less at higher temperatures, changing the nature of deformation under stress. Departure from perfectly uniform stress distribution is caused by mechanical inhomogeneities such as inclusions and flaws, often microscopic in size, and by end effects in loading the specimen. As soon as deformation begins, which may be at very low loads, cold working phenomena enter, introducing further departures from true homogeneity. Tempering effects, or crystalline readjustment, occur in connection with this

cold-worked material, time being an important factor as well as temperature. That perceptible permanent deformation may occur at extremely low loads, has been shown whenever methods of high accuracy were used in measurements. Gradual recovery after perceptible flow or slip is also to be reckoned with.

Mr. Foley speaks of "true elastic limit" and "true proportional limit". The values obtained for these properties seem to depend upon the precision of the methods and apparatus used in determining them, and there is reason to believe that the true values may be zero. Exceeding true elastic limit, supposing there is one, does not necessarily imply continued plastic flow without increase in load, because of the increased strength produced by cold work. An example is the use of lead pipe carrying moderate water pressure. Lead has no appreciable elastic limit and yet the pipe does not swell up and burst. As temperature is raised, crystalline readjustment increases and deformation becomes hot working. We might then expect continuous plastic flow.

The factors of time and temperature introduce the question of metallographic stability or equilibrium. This includes grain growth, particle growth, precipitation and solution, as well as crystalline readjustment after cold work. Such changes take place at room temperature. Room temperature obviously is a tempering temperature and an elevated temperature in a true sense. The effect of raising temperature is ordinarily to amplify phenomena which are present at room temperature; phenomena which are or could be detected by methods sufficiently accurate. It might clarify our reasoning to refer all data back to a base line of absolute zero, considering room temperature as an elevated temperature instead of a base line. In the whole matter we are forcefully reminded of the relativity of all things.

It has been said that the steel industry is twenty years behind the times in pure research. Study of an exaggerated or an extreme case often helps us to understand more clearly the normal case. Tests at elevated temperatures on metals may in this way help us to get a truer understanding of the nature of metals. There would seem to be no line of pure research more worthy of our attention than this.

H. J. FRENCH: The title of this paper relates to a subject which is still controversial. On this account it may be of interest to give briefly some of the salient features developed from recent experiments which we have made on steels.

Extended creep tests clearly indicate that allowable safe working stresses not only depend upon the temperature encountered and steel used but also upon the criterion of satisfactory performance. For the conditions of substantially constant temperature and a fixed applied load and provided chemical inertness is disregarded, satisfactory performance may be resolved into the maximum allowable deformation during some selected minimum time.

If this criterion permits, say, 1 per cent deformation in 1000 hours, the allowable stress would be higher than that for a smaller permissible deformation or longer life or both. In other words the relations between

creep and temperature for a selected steel may be represented by a family of curves which represent the deformation per unit of time, or conversely, the length of time required for a selected deformation to be produced. These curves cross lower and lower stress values at any selected temperatures as the requirements of freedom from deformation and increase in life become more severe.

A similar situation is found in the results of the stress-strain measurements in tension tests at different temperatures. Proportional limits determined with moderately sensitive extensometers are generally at higher stresses than those determined with very sensitive instruments under otherwise comparable conditions. If different orders of departure from the apparent proportionality between stress and strain are plotted aga. / , temperature a family of curves is secured which resembles in many ways the family of curves obtained from the laborious creep tests.

For the steels which have so far been tested, proportional limits determined with extensometers reading directly to a few millionths of an inch are within the range of stresses at which the steels show only small amounts of deformation in relatively long periods. Of course, there are practical difficulties in making reproducible determinations of the proportional limit under such conditions. For these and others reasons substitution of refined tension tests for creep tests is not advocated but past experience indicates that the stress-strain relations in short time tension tests should be considered along with creep tests as this may be productive of useful data.

W. J. MERTEN: I would like to put my discussion in the form of a question to Mr. Foley. If I understood his paper aright, one would expect an alloy steel of a low coefficient of expansion to be of fairly high proportional limit at high temperatures. That is not always the case, however, and I am wondering whether he does not suspect some chemical phenomenon masking the reaction?

F. B. FOLEY: It seems to me quite difficult to separate chemical and physical conditions when we are talking about atoms but I do not suppose it follows that if you have a low coefficient of expansion, that you necessarily would have a steel that had a high proportional limit at elevated temperature. It would merely mean that at the slope of the curve obtained in plotting the total separation of atoms, one from another at the proportional limit against temperature, would be changed, but it would not, I suppose, change the proportional limit necessarily.

W. J. MERTEN: Mr. Foley, I have in mind right now the question of the salt bath. There is a very little load when you consider a layer of salt about four or five inches deep imposing on the plate, causing considerable deformation known as bulging, you certainly have chemical as well as physical reactions to consider, in such cases, the loads are not any higher than those which you are indicating as very low.

F. B. FOLEY: I am beginning more and more to grasp what you mean, but that depends entirely on temperature. If the temperature is high enough it will not sustain much load, and the higher the heat the lower the proportional limit becomes and ultimately it reaches a very low value and the

material becomes practically a viscous mass. That is not, I think, the meaning of those who have been talking about deformation at very low stresses. I think they mean that metal with a proportional limit determined at elevated temperatures we will say of the order of 8, 9 or 10 thousand pounds, might flow under a load of only ten, fifteen or twenty pounds. However, that is, I think, not important.

W. J. MERTEN: I was applying your theory to practical problems.

F. B. FOLEY: I think you are perfectly right, if the temperature goes high enough.

W. J. MERTEN: The temperatures I am referring to are not higher than 1500 or 1600 degrees Fahr.

Author's Closure

Mr. McVetty and Mr. French both bring out clearly and concisely the limitations in the present methods of determining the physical properties at elevated temperatures and Mr. French quite properly points out the limitations of the application of properties so determined. The point which we aim to develop is that at present we are faced with the problem of determining the available strength at elevated temperatures of so many different compositions of steel in a great variety of metallographic conditions and that we are proceeding to attack the problem in a purely mechanical way. To the question, "What proportional limit will such and such a steel give at 1000 degrees Fahr.?" our only reply today is, "Try it and see." Certainly it is essential that a great quantity of data bearing on the change in physical properties of metals under the influence of heat must be obtained in order to arrive at a mathematical expression which will predict the properties to be reasonably expected from a given composition of steel the properties of which at room temperature are known.

Mr. Knerr directs attention to the lack of uniformity of stress distribution during testing. That is a source of error, no doubt, but one that all tensile testing is more or less subject to. While, as he points out, the properties of a crystal differ according to the orientation of the planes within it we are forced in an aggregation of crystals to use an average value—which, in the long run, is the value which produces the effects which we measure. These factors all have their influence on any analysis of crystal deformation which we may choose to undertake. That grain boundary metal "partakes of the nature of an under cooled liquid or vitreous amorphous material" is questionable. It is a condition which has been postulated to account for certain phenomena which are not readily accounted for otherwise, and all attempts to prove the existence of such a grain boundary condition have failed.

Stressing below the proportional limit is probably not accompanied by cold nor hot working, nor does it produce a work hardening effect. Certainly, it is conceivable that a limiting spacing within which atoms may be temporarily displaced, returning to their original spacing when the displacing load has been removed, may exist.

EXPANSION CHARACTERISTICS OF LOW-EXPANSION NICKEL STEELS

By Howard Scott

Abstract

An expansion test apparatus with which continuous thermal expansion curves can be obtained with good accuracy from liquid air temperature to 1110 degrees Fahr. (600 degrees Cent.) is described.

Expansion curves were taken on a series of low-expansion nickel steels and synthetic iron-nickel alloys. The results were reduced to convenient tabular form and plotted to show the variation of the chief expansion characteristics with nickel content.

The detrimental effect of manganese and silicon on the expansion properties was shown and the values of these properties estimated for zero per cent manganese and silicon. The advantage of cold working to reduce the coefficient of expansion was confirmed.

Introduction

THE low-expansion nickel steels, being relatively inexpensive, find many applications in industry. For example, they are used in thermostat metal; in "dumet", a duplex wire, having the same coefficient of expansion as glass; and for length standards. Extension of their applications requires a more exact knowledge of their expansion characteristics than appears in the published literature. This situation led to a further study of their properties, with special reference to the effects of the normal elements entering into their composition and to the expansion as a function of temperature.

The low-expansion characteristic of high-nickel steels is unique and finds no analogue in any other alloy system. In place of a high expansion alloy which would be expected with increasing additions of nickel to iron, alloys having a very low coefficient of expansion over a considerable temperature range are obtained. No satisfactory

A paper presented before the ninth annual convention of the society held in Detroit, September 19 to 23, 1927. The author, Howard Scott, a member of the society, is connected with the research department of the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa. Manuscript received August 19, 1927.

explanation of this anomaly has yet appeared in the literature. Benedicks[1] has made a careful analysis of the problem and proposed an explanation of the phenomenon. According to his theory, the high nickel steels, contrary to the current impression, represent a two-phase system such as is found in meteorites. The constituents are believed to be much more finely divided than in meteorites and to differ in nickel concentration only. Presumably the usual fabrication methods do not permit the representative meteorite structure to develop into plain visibility.

Benedicks assumes that the phase having the lower nickel content has a large negative coefficient of expansion and that having the higher nickel concentration has a large positive coefficient. The large positive coefficient would, of course, be expected when the nickel content is high enough to repress the gamma to alpha transformation of iron below ordinary temperatures. The negative coefficient, an increase in volume with decreasing temperature, is attibuted to this transformation which occurs at a higher temperature in the phase poorer in nickel. Obviously any coefficients between the limiting positive and negative values could be obtained by varying the ratio of the constituent phases.

On the basis of the known time lag of phase changes, Benedicks predicts that a low mean coefficient will be found only for slow rates of heating and cooling. He found experimental evidence of this effect from high sensitivity expansion tests, but no such an effect was noted here in spite of a rather close, though unintentional, correspondence of heating conditions. This matter will be discussed later; for the present it will suffice to say that the plausibility of this theory is lessened by the known extremely large hysteresis of the gamma-alpha transformation in high nickel steels and by the fact that this transformation is depressed below liquid air temperatures in invar. A concentration gradient of 12 per cent nickel would be necessary to bring one phase into the alpha state in invar.

There are two impressive features of the low-expansion anomaly which offer promising suggestions as to the fundamental nature of the phenomenon. First, the low-expansion alloys are magnetic cold, but lose their magnetism rather abruptly on heating above a certain temperature called the Curie point. Concur-

[1]Metallographic Researches—Benedicks. McGraw-Hill, 1926.

rently with the loss in magnetism, the coefficient of expansion increases rapidly to a high value which would normally be expected in a non-magnetic iron alloy.

Second, Gruneisen[2] has established, on theoretical grounds, the law that the coefficient of expansion divided by the heat capacity is a constant for a particular metal in the solid state independent of temperature. This law has been confirmed for pure metals and recently for iron-nickel steel as well.[3] Suggestive as these relations are, no adequate explanation has yet been offered for the low-expansion characteristics of nickel steels.

Expansion Test Method

The abrupt increase in the coefficient of expansion of these alloys at the Curie point is of considerable importance in the technical use of these alloys. To locate this change requires a practically continuous expansion curve. Also a high sensitivity is required because of the small coefficient met with. Of the standard expansion test methods, the high precision method of the Bureau of Standards is out of the question because of the long time required for each observation. On the other hand, there is on the market a differential expansion test apparatus which traces a continuous curve photographically. As this apparatus was not as flexible and accurate as was desired, a special apparatus was constructed to meet the requirements mentioned. Incidentally, the new apparatus permits continuous expansion measurements from liquid air temperatures to at least 1110 degrees Fahr. (600 degrees Cent.) without any difficulty.

Fig. 1 gives the essential features of this apparatus. A mechanical length-change indicator measures the movement of one end of the specimen relative to the silica tube container. The motion is transmitted from the specimen end to the indicator by the inner silica tube: Specimens 4 inches long, ¼ inch in diameter, having the ends turned to a radius of ⅛ inch, were used. The specimen is held vertically in the tube by a spring which presses it into a V-groove. In order to obtain positive contact between the inside tube, the specimen and the indicator, both ends of the inside tube were lapped to a cone shape as indicated. The lower

[2] Ann. der Phys. 26: 211 (1908).

[3] M. Kawakami: Science Reports, Tohoku Imperial University 15: 251 (1926).

half of the apparatus (a length of approximately 9 inches) was heated. The temperature of the specimen was measured by a "chromel-alumel" thermocouple (0.016-inch diameter wire) the hot-junction of which was spot-welded to the middle of the specimen.

The novel feature of this apparatus was the use of a small and inexpensive dial gage to measure the difference in length-change

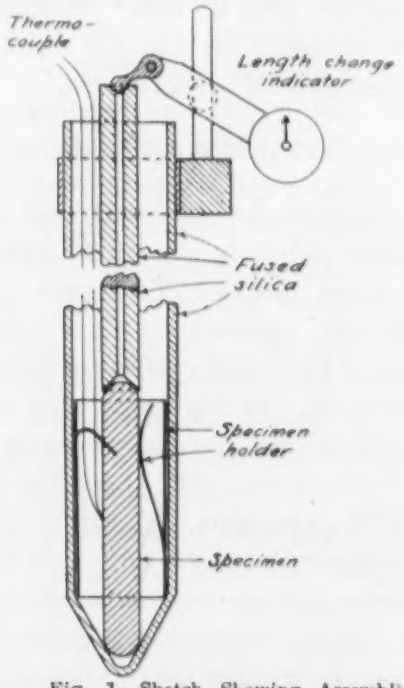


Fig. 1—Sketch Showing Assembly of Expansion Test Apparatus.

between the specimen and its silica tube container. The indicator covers a range of 0.035 inch and may be read to 0.0001 inch. This range and sensitivity was found to be sufficient for the intended use. The sensitivity can, of course, be increased by using a longer specimen, but a short specimen was chosen in order to reduce errors due to temperature gradients in the specimen which might otherwise become objectionably large when taking observations during continuous heating and cooling as planned.

The following sources of error may be recognized in this method:

1. Indicator calibration.
2. Change in angle of indicator lever arm.
3. Lost motion.
4. Thermocouple calibration

5. Temperature gradient from sample to thermocouple
6. Temperature gradient along length of specimen.
7. Expansion of silica.
8. Variation of temperature differences between inner and outer silica tubes.
9. Length of specimen.
10. Transverse expansion of specimen.

These possible errors were treated as follows:

(1) The indicator was calibrated in comparison with a micrometer head and found to read 2 per cent low for a lever arm angle of 15 degrees from the normal to the inside tube. No correction was made for this error.

(2) As the angle of the lever arm of the indicator increases with expansion, the effective lever length is reduced giving a high reading. The error increases proportionally to one minus the cosine of the angle. Starting with an angle of 15 degrees, the error is -2 per cent, but when the deflection reaches the end of the indicator scale, it is $+2$ per cent. Hence these errors more or less neutralize each other and are consequently neglected. Care must be taken, however, that the initial lever arm angle is not greater than 15 degrees.

(3) Lost motion in the type of indictor used is negligible, but some may occur in the assembled apparatus. This error is avoided by neglecting the first few readings at the beginning of heating. This also takes care of the temperature differences initially established between the inside and outer silica tubes.

(4) The accuracy of the thermocouple used was $\pm$ 1 degrees Cent. with the cold-junction in ice. The accuracy of the length-change measurements does not require any greater accuracy of temperature measurement.

(5) A temperature gradient between thermocouple hot-junction and specimen would cause the expansion curve on heating to be lower than that on cooling. A displacement in this direction was never observed.

(6) A linear temperature gradient along the specimen would cause no error so long as the coefficient did not change rapidly. A non-linear gradient is possible during the start of heating or cooling because of the good thermal contact between the specimen and bottom of the tube. Actually this error is appreciable only during cooling in liquid air when the initial rate of cooling is very rapid. Under these circumstances the cooling curve falls

below the heating curve. To avoid error from this source, reduced observational data is taken only from heating curves taken during slow heating, usually less than 3 degrees Cent. per minute.

(7) The apparent expansion of the specimen is lower than the true by the expansion of the same length of silica. The expansion curves, with a few expansions, give the differential expansion, but the plotted coefficients and tabulated data are corrected for the expansion of silica as determined by Souder and Hidnert.[4]

Table I

Comparison of Expansion Data from Differential Test with that from High-Precision Test of High-Expansion Alloy

Temp. °C.	Unit Expansion (x 10^{-3}) Differential Method	High Precision	Coefficient (x 10^{-6}) Differential Method	High Precision
—100	—1.57	.....	11.8	.....
0	0	0	18.2	18.16
+100	+1.89	+1.88	19.5	19.50
200	3.89	3.90	20.5	20.83
300	6.01	6.05	22.2	22.17
400	8.37	8.33	23.8	23.50
500	10.72	10.75	24.5	24.84

(8) As the coefficient of expansion of silica is very low, 0.5×10^{-6} degrees Cent., error due to changing temperature differences between the inner and outer tubes is negligible except possibly at the start of heating. The error at the start is obviated in the reduced data by neglecting the initial expansion readings.

(9) Because of the shape of the specimen, its active length cannot be measured accurately. However, it can certainly be measured to 1 per cent.

(10) The bottom of the outer silica tube slopes at an angle of about 30 degrees to the axis of the specimen. Consequently transverse expansion of the specimen is converted into longitudinal expansion about 1.7 times greater. This may be corrected for by subtracting 5 per cent of the expansion of the ¼-inch diameter specimen. As the expansions dealt with here are very small, this correction was neglected.

In order to be certain that the errors mentioned were fully accounted for, expansion tests were made on a high-expansion metal which was tested by a high-precision method as well. The

[4]Souder & Hidnert—Bureau of Standards Scientific Paper No. 524.

high-precision test was made with apparatus of the Bureau of Standards type by Mr. Schad of this laboratory. The results of the comparison are given in Table I. The values by the differential

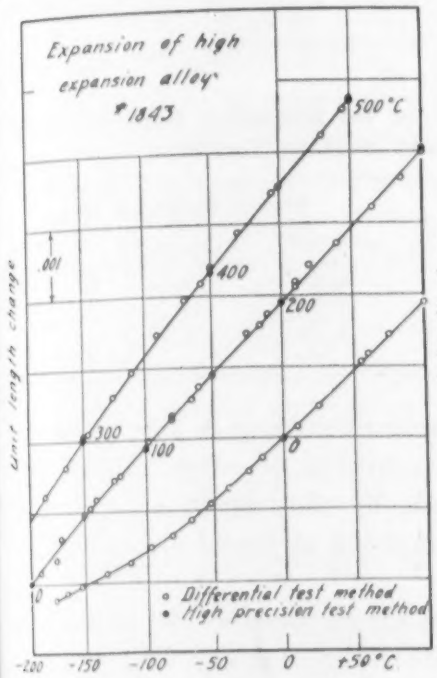


Fig. 2—Comparison of Expansion Observations by Differential Test with Observations by High-Precision Test on a High-Expansion Alloy.

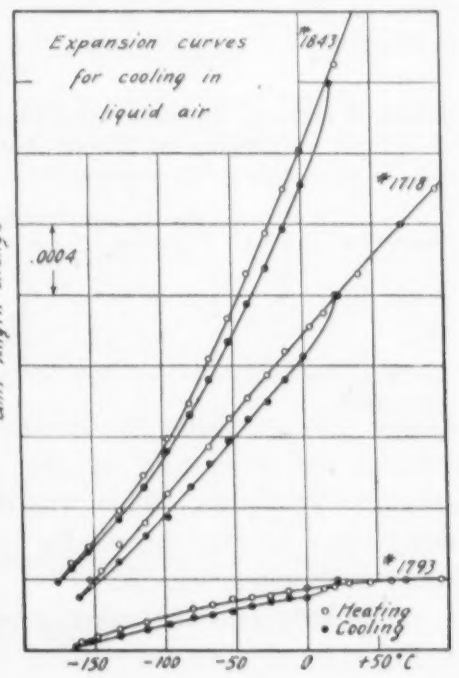


Fig. 3—Expansion Curves Taken During Cooling in Liquid Air and Heating Thereafter.

test are of course corrected for the expansion of silica and for the transverse expansion of the specimen. The data of the high-precision test were taken from the equation:

$$\frac{L_T}{L_0} = 1 + (18.16T + .00668T^2) \times 10^{-6}$$

the constants of which were determined from expansion observations at five temperatures between 75 and 930 degrees Fahr. (500 degrees Cent.). The data from the differential test were taken from the curve representing the observational points plotted in Fig. 2. From the good agreement of the two tests it appears that the corrections mentioned are adequate over the temperature range 25 to 500 degrees Cent.

No check on the expansion test method was available below ordinary temperatures. As the expansion of silica is practically

zero below 0 degrees Cent., error due to the direct or differential expansion of the silica tubes may be neglected. The direct introduction of the outer silica tube in liquid air, however, leads to appreciable errors due to temperature gradients during cooling.

Table II

Effect of Rate of Temperature Change on the Expansion Hysteresis During Cooling in Liquid Air and Heating Thereafter

Temp. °C.	Rate of Temperature Change (°C./min.) Cooling	Heating	Sum	Between Heating and Cooling Expansion Difference (x 10^{-3}) No. 1843	No. 1718	No. 1793
0	30	3	33	0.21	0.13	0.04
—50	24	5	29	0.14	0.13	0.05
—100	12	8	20	0.06	0.09	0.05
—150	4	16	20	0.03	0.03	0.02

Under this condition the initial rate of cooling is very rapid and permits an estimation of the magnitude of error due to temperature gradients. This was done by plotting to an open scale cooling and heating curves for immersion in liquid air and heating in air thereafter, Fig. 3.

The hysteresis between expansion on heating and cooling can be interpreted once the cooling rate is determined. This was done from the time-temperature curve of specimen No. 1843 and the

Table III

Comparison of Coefficients of Expansion Taken During Cooling in Liquid Air with Those Taken During Heating Thereafter

Temp. °C.	Rate of Cooling (°C./min.)	Rate of Heating (°C./min.)	Coefficient of Expansion (x 10^{-6}) Alloy No. 1793 Cooling	Htg.	Alloy No. 1718 Cooling	Htg.	Alloy No. 1843 Cooling	Htg.
0	30	3	1.4	1.2	9.2	9.0	18.0	18.8
—50	24	5	1.7	1.5	9.0	9.4	15.4	17.2
—100	12	8	1.9	2.1	8.2	9.4	12.0	12.0
—150	8	16	2.0	2.7	6.8	9.2	8.0	9.0

cooling rates given in Table II. The significant fact presented in this table is that the difference in expansion between the heating and cooling curves is large only at the start of cooling of a specimen of high coefficient of expansion. The small difference, 0.02 to 0.05×10^{-3} for the low-expansion alloy No. 1793, may be attributed to lost motion and to differential heating of the silica tubes. This appears as a component of the high coefficient alloys as well.

As the coefficient is little affected by the rate of heating, the presumption is that the accuracy of the observations below ordinary temperatures is equal to that above and that there is no hysteresis in the expansion itself greater than 0.01 per cent of the length.

The curves of Fig. 3 are of interest also because of their bearing on Benedicks' theory of the low-expansion anomaly. His

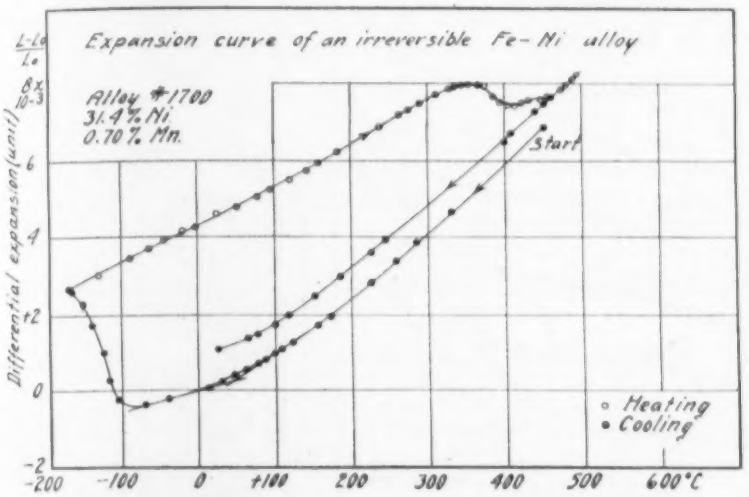


Fig. 4—Expansion Curves Showing Transformations on Heating and Cooling of an Irreversible Iron-Nickel Alloy.

theory requires and he has observed a high coefficient on rapid heating or cooling of invar compositions. Such was not found for cooling rates of the magnitude used by him, 30 degrees Cent. per minute. Table III. The effect described by him must, therefore, be attributed to temperature lag between his specimen and temperature measuring device. Such a difference is easily possible due to the entirely different thermal properties of the specimen and of the temperature measuring blank, which was platinum.

Experimental Results

The iron-nickel alloys used here were melted in a high-frequency induction furnace from electrolytic iron and electrolytic nickel. Manganese was added, generally 1 per cent in order to obtain forgeable alloys. In some cases a small quantity of aluminum or ferrotitanium was added to degasify. All specimens were tested as hot-formed or annealed, unless otherwise stated.

The compositions of the alloys studied are given in Table IV. The nickel plus cobalt content is given because of the difficulty

of separating nickel and cobalt. A few determinations of cobalt showed less than 0.2 per cent in the synthetic alloys and less than 1.0 per cent in commercial steels. To this extent cobalt has no appreciable effect on the expansion beyond that of an equivalent

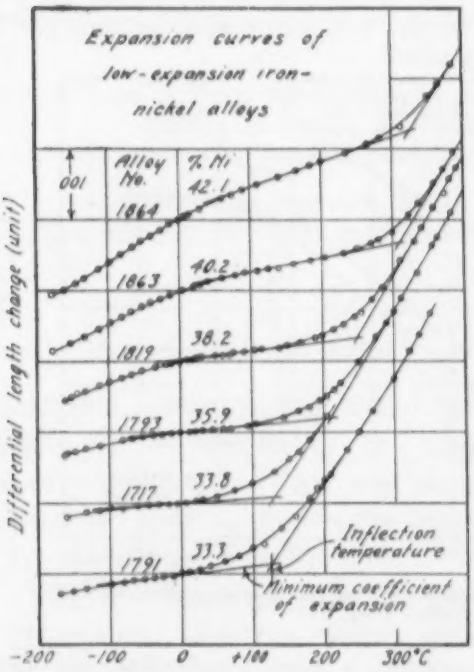


Fig. 5—Expansion Curves of Reversible Low-Expansion Iron-Nickel Alloys. Nickel Contents from 33 to 42 Per Cent.

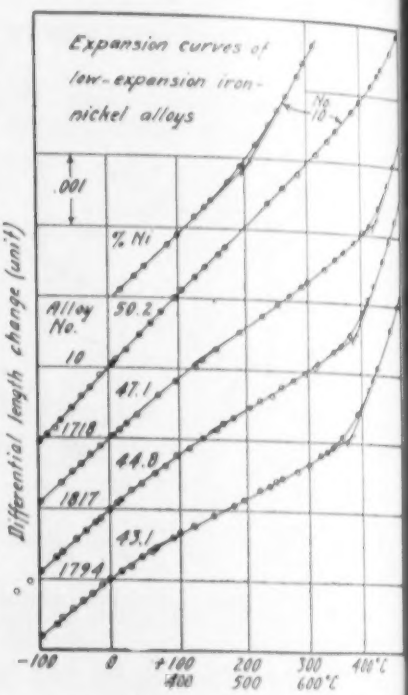


Fig. 6—Expansion Curves of Reversible Low-Expansion Iron-Nickel Alloys. Nickel Contents from 43 to 50 Per Cent.

content of nickel. Consequently, reference to the nickel content will imply the nickel plus cobalt content when the cobalt is under 1 per cent.

The low-expansion characteristic of nickel steels appears only when the gamma to alpha transformtion of iron is depressed below ordinary temperatures by alloying additions. This is illustrated by Fig. 4, which gives a complete expansion curve for a nickel steel in which the gamma to alpha change occurs between ordinary and liquid air temperature. A large increase in volume occurs with this transformation. On re-heating the reverse change, alpha to gamma, does not occur until 660 degrees Fahr. (350 degrees Cent.) is reached. Hence it is called the "irreversible transformation" to distinguish it from the reversible transformation at the Curie point. Some 30 per cent nickel is necessary to depress this transformation well below normal temperatures. In the low-expansion

nickel steels, the nickel content is generally well above 30 per cent so that the irreversible transformation is of no concern. The reversible transformation, however, is of considerable importance because of the limit it places on the temperature range of low expansion. Hence particular care was taken to define its characteristic temperatures.

As the expansion changes continuously through the irreversible transformation, it is difficult to pick a temperature characteristic of

Table IV

Composition and Chief Expansion Characteristics of Nickel Steels and Synthetic Iron-Nickel Alloys as Hot-worked or Annealed

Specimen No.	Chemical Composition % Ni	% Mn	% Si	% C	Inflection Temp. (°C.)	Minimum Coefficient of Expansion	Temperature Range of Low Coefficient (°C.) Minimum	Maximum
	Commercial Steels							
13	37.24	0.73	0.18	0.08	255	2.2×10^{-6}	— 10	+130
17	36.49	0.22	0.05	0.09	245	1.0	— 10	+130
182	38.2	0.69	0.14	0.12	275	2.2	+ 40	+170
165	43.10	0.90	0.15	0.12	365	5.4	+150	+300
181	42.80	0.89	0.08	0.11	365	5.3	+120	+310
	Synthetic Alloys							
1700	31.36	0.70	....	0.03	50	7.0	.....	.....
1791	33.31	0.88	0.01	0.03	125	1.3	—150	— 20
1717	33.83	0.88	....	0.02	130	1.1	—150	0
1793	35.89	0.87	0.01	0.02	190	1.2	— 50	+ 70
1819	38.17	1.00	0.05	0.03	245	1.6	+ 20	+130
1863	40.17	0.80	0.004	0.01	310	2.4	+ 70	+210
1864	42.12	1.54	0.004	0.01	325	3.9	+110	+250
1794	42.76	0.92	0.01	0.01	375	5.5	+110	+280
1817	44.77	1.08	0.07	0.03	385	6.2	+180	+330
1718	47.09	0.82	....	0.01	420	7.3	+150	+370
10	50.19	0.64	0.02	0.00	500	9.6	+160	+420
	Ternary Alloys							
1912	45.16	0.53	0.066	0.033	420	6.5	+200	+370
1913	45.43	1.96	0.061	0.013	385	6.9	+190	+350
1914	45.43	5.03	0.145	0.020	325	7.7	+180	+290
1915	45.31	0.67	0.830	0.016	390	6.3	+200	+360

this change. This difficulty is avoided by taking the intersection of the slope of the expansion curve representing minimum coeffiicent of expansion with that representing the coefficient just above the end of the change. This temperature is called the "inflection temperature" and its definition is illustrated by Fig. 5. By calling this change an inflection we avoid the implication of a change in crystal structure which is usually associated with transformation. The inflection, as previously noted, is characterized by a rapid change in coefficient of expansion, heat content and magnetizability, but it lacks entirely other manifestations of lattice reconstruction such as hysteresis and abrupt changes in other physical properties.

The inflection temperature is a definite measure of the limit

of low expansivity. A single value representative of the expansivity of alloys is also desirable for condensing experimental results. This is furnished by the minimum coefficient of expansion. Values of the inflection temperature and minimum coefficient of the

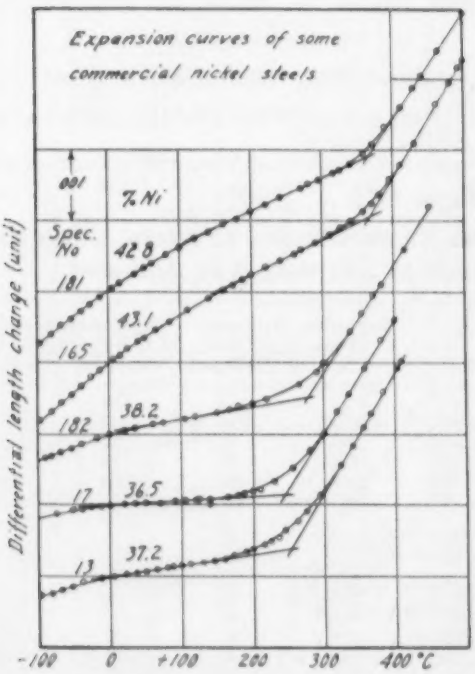


Fig. 7—Expansion Curves of Some Commercial Low-Expansion Nickel Steels.

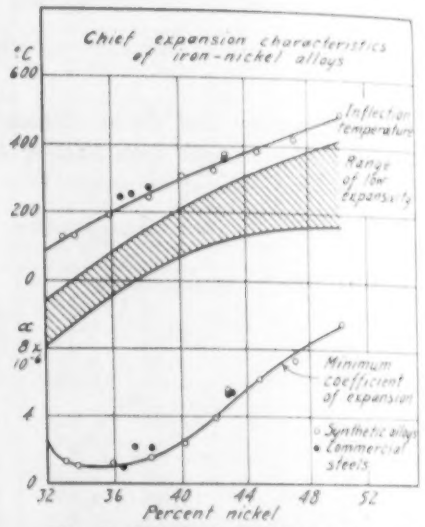


Fig. 8—Effect of Nickel Content on the Inflection Temperature, Minimum Coefficient of Expansion and Temperature Range of Low Coefficients of Expansion.

iron-nickel alloys have been taken from Figs. 5 and 6 and are given in Table IV. The same thing has been done for several commercial steels, the expansion curves of which appear in Fig. 7.

The inflection temperatures and minimum coefficients of both the synthetic alloys and the commercial steels are plotted against nickel content in Fig. 8. These curves show that both properties increase rapidly with nickel content from the invar composition, about 36 per cent nickel. The increase in coefficient is 0.75×10^{-6} (degrees Cent.) per per cent nickel and in the inflection temperature 20 degrees Cent. per per cent nickel between 40 and 50 per cent nickel. Consequently the low expansion of invar is not available at high temperatures in any alloy.

To show more clearly the temperature limits within which the low-expansion characteristic of any alloy is available, it was necessary to plot values of the coefficient against temperature for several

alloys as in Figs. 9, 10 and 11. From these curves, the temperature limits between which the coefficient does not change more than 0.5×10^{-6} were taken as given in Table IV and plotted in Fig. 8.

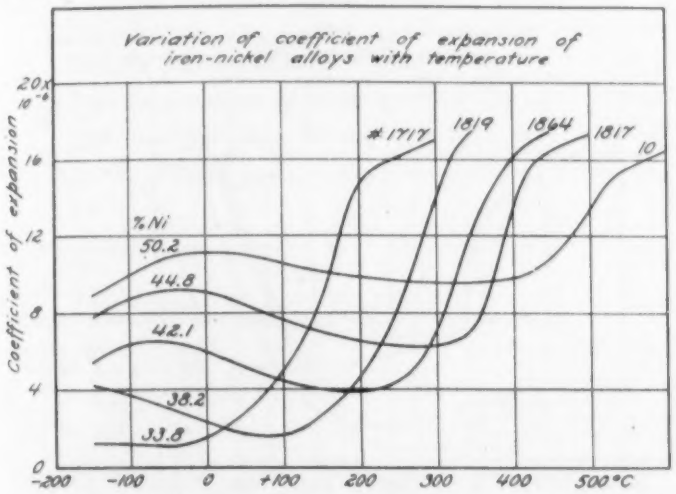


Fig. 9—Variation of Coefficient of Expansion with Temperature. Curves for Synthetic Iron-Nickel Alloys Containing 34 to 50 Per Cent Nickel and About 0.9 Per Cent Manganese.

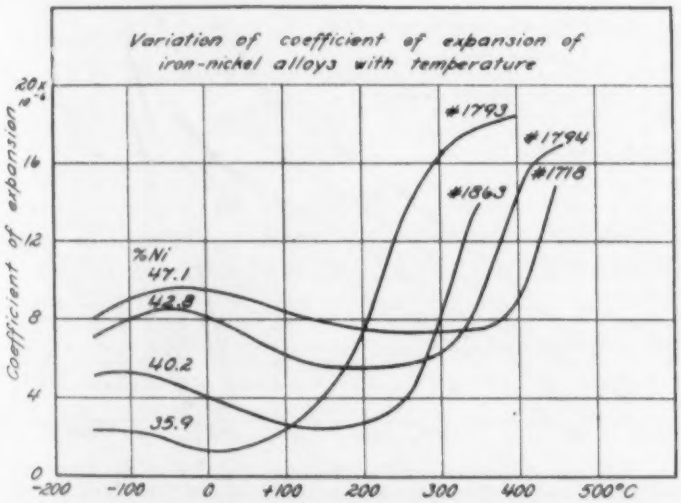


Fig. 10—Variation of Coefficient of Expansion with Temperature. Curves for Synthetic Iron-Nickel Alloys Containing 36 to 47 Per Cent Nickel and About 0.9 Per Cent Manganese.

Now the range of utility of any composition can be determined directly from this figure.

Of particular interest is the low minimum coefficient obtained with one commercial steel, specimen No. 17, which is equal to our best synthetic alloys. So low a coefficient is unusual for invar

compositions made in this country. Reference to the composition in Table IV shows that this steel is particularly low in manganese. Evidently nickel steels can be hot-worked with so low a manganese

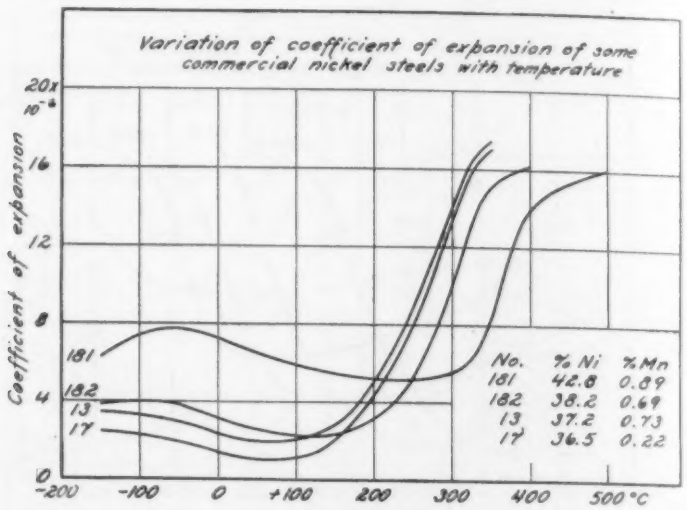


Fig. 11—Variation of Coefficient of Expansion of Some Commercial Nickel Steels with Temperature.

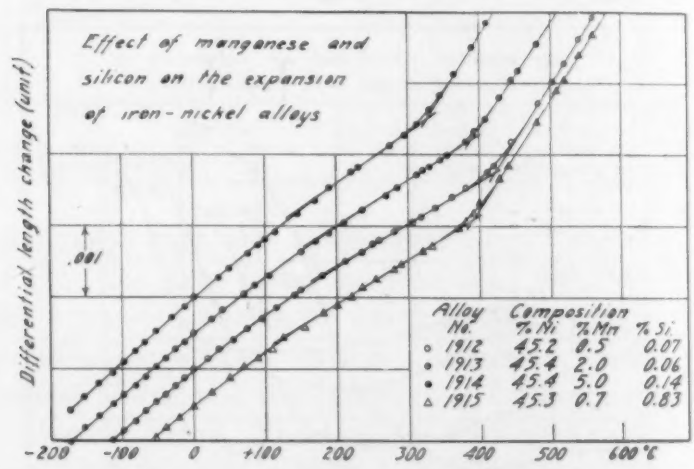

Effect of manganese and silicon on the expansion of iron-nickel alloys
Differential length change (unit)
.001
Alloy No. Composition % Ni % Mn % Si
○ 1912 45.2 0.5 0.07
● 1913 45.4 2.0 0.06
● 1914 45.4 5.0 0.14
△ 1915 45.3 0.7 0.83
-200 -100 0 +100 200 300 400 500 600 °C

Fig. 12—Expansion Curves Showing the Effect of Manganese and Silicon on the Expansion Properties of 45 Per Cent Nickel Steel.

content. It is possible, however, that some element, undetected by our chemical analysis, was added to neutralize the red shortness conferred by sulphur.

The effects of the normal components of steel are known to be injurious to the expansivity of iron-nickel alloys. Guillaume has shown this as regards the coefficient at normal temperatures (B. of S. Circular No. 58). These alloys, however, are used over a

wide range of temperatures, so the effect of the more essential foreign elements, manganese and silicon, was studied. The expansion curves of alloys containing about 45 per cent nickel and various percentages of manganese and silicon are given in Fig. 12 and the

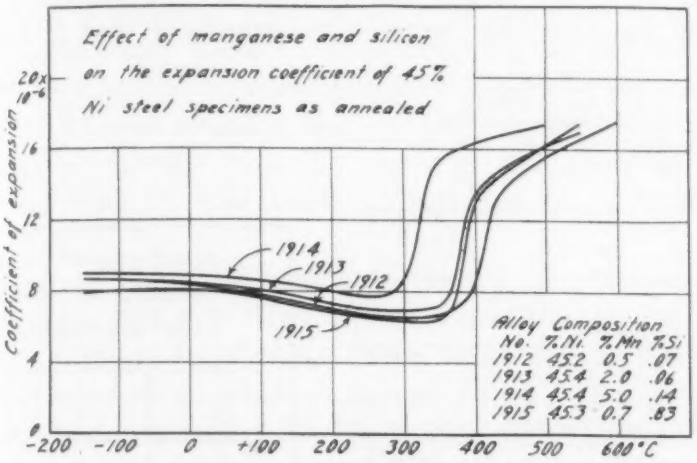


Fig. 13—Effect of Manganese and Silicon on the Coefficients of Expansion of 45 Per Cent Nickel Steel Plotted Against Temperature.

derived curves of the coefficient of expansion in Fig. 13. The effect of these elements on the inflection temperature and minimum coefficient is quite pronounced. Quantitatively 1 per cent manganese lowers the inflection temperature 20 degrees Cent. and raises the

Table V

Effect of Annealing After Cold-Swaging Specimen No. 13 (37.2 Per Cent Nickel; 0.73 Per Cent Manganese)

Annealing Temp. °C.	Inflection Temp. °C.	Minimum Coefficient	Temperature Range of Low Coefficient (°C.) Minimum	Maximum
25	235	0.7	0	+100
400	240	1.4	0	110
600	255	2.3	0	120
800	250	2.1	0	140

coefficient by 0.26×10^{-6}, while 1 per cent silicon lowers the inflection temperature 30 degrees Cent. but does not affect the coefficient appreciably.

Assuming these effects of manganese and silicon are independent of nickel content, the inflection temperatures and coefficients of expansion were calculated for 0 per cent manganese and silicon. These values were plotted against each other in Fig. 14 to

eliminate chemical effects. Both properties are determined physically, hence the proximity of the points to the representative curve is a measure of the reliability of the test method provided the elements outside of nickel are reasonably constant.

Another more important feature of the minimum coefficient inflection temperature curve is the standard that it supplies for

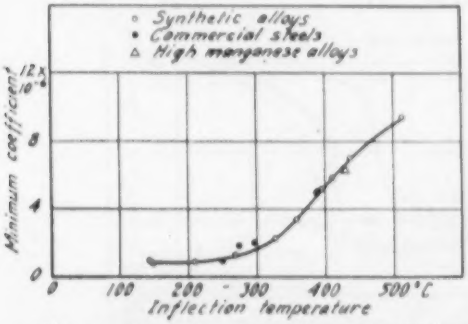


Fig. 14—Variation of Minimum Coefficient of Expansion with Inflection Temperature for Hypothetically Pure Iron-Nickel Alloys. Points to the Left or Above This Curve Represent Inferior Expansion Properties; to the Right or Below, Superior Expansion Properties.

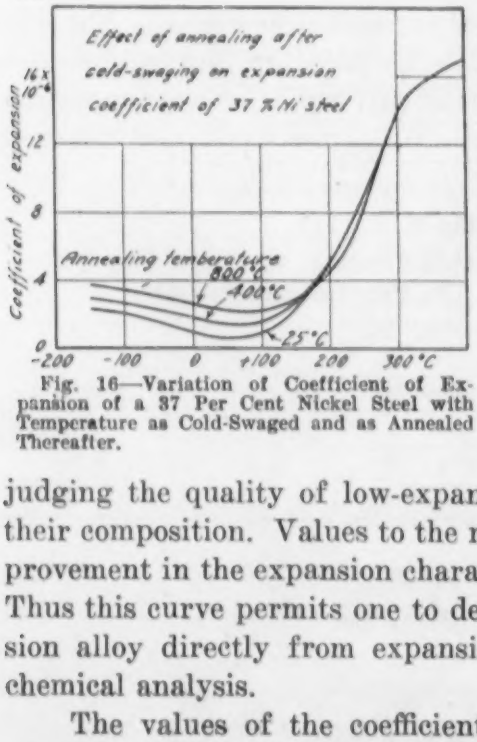


Fig. 16—Variation of Coefficient of Expansion of a 37 Per Cent Nickel Steel with Temperature as Cold-Swaged and as Annealed Thereafter.

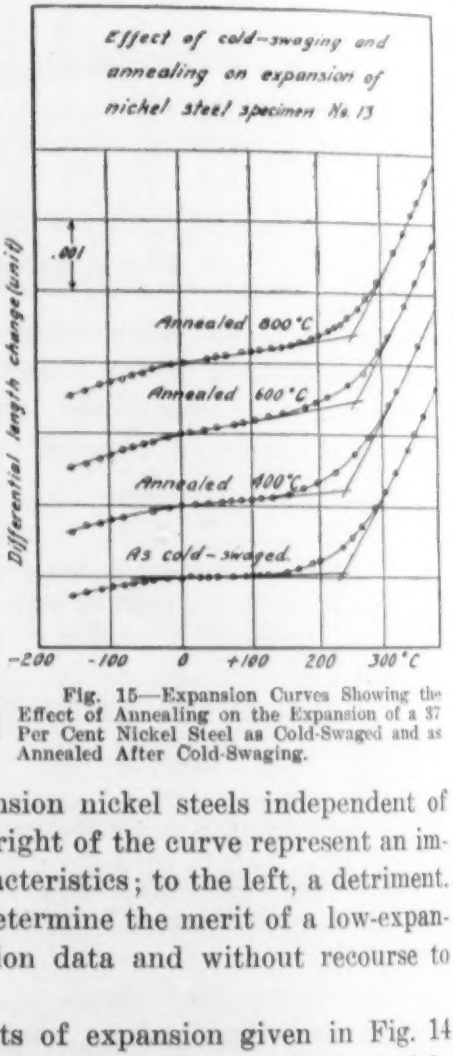


Fig. 15—Expansion Curves Showing the Effect of Annealing on the Expansion of a 37 Per Cent Nickel Steel as Cold-Swaged and as Annealed After Cold-Swaging.

judging the quality of low-expansion nickel steels independent of their composition. Values to the right of the curve represent an improvement in the expansion characteristics; to the left, a detriment. Thus this curve permits one to determine the merit of a low-expansion alloy directly from expansion data and without recourse to chemical analysis.

The values of the coefficients of expansion given in Fig. 14 represent the best coefficients that can be expected from straight iron-nickel alloys in the hot-formed or annealed condition. Their

coefficients, however, can be materially improved by cold working. So far as the writer knows, a zero or negative coefficient has never been obtained in the iron-nickel system without cold working.

The effect of cold working and annealing thereafter on the expansion of a commercial steel near invar composition is shown in Fig. 15. Coefficients taken from these curves are plotted against temperature in Fig. 16. The minimum coefficient is reduced from 2.2 to 0.7×10^{-6} by cold swaging from ¼ to ⅛ inch diameter, Table V. This agrees exactly with the value of the lowering due to quenching followed by cold working, reported in B. S. Circular No. 58 (p. 38).

The range of low coefficient, however, is shortened somewhat by cold working, but this effect is not objectionable for a given mean coefficient is available over a much longer temperature range in the cold-worked metal than in the annealed. This would lead one to expect that a zero or negative minimum coefficient could be obtained around normal temperatures with the nearly pure commercial nickel steel, specimen No. 17, by cold working, although the experiment has not been made.

This paper is presented chiefly for the new information contained on the expansion of nickel steels as a function of temperature, but the occasion is taken to describe a simple and effective expansion test method. The increasing use of metals at elevated temperatures has brought to metallurgists the need for such an expansion test method. The apparatus described, from the experience obtained with nickel steels, appears particularly adapted to metallurgical demands of an expansion test method.

Summary

A simple and inexpensive differential expansion test apparatus with which continuous expansion curves can be made from liquid air temperature to 1110 degrees Fahr. (600 degrees Cent.) or more is described. As used here coefficients of expansion can be measured with an accuracy of about $\pm 0.2 \times 10^{-6}$ (degrees Cent.). This is satisfactory for most metallurgical requirements.

Expansion curves of a number of synthetic iron-nickel alloys and commercial nickel steels containing from 30 to 50 per cent nickel were taken. The characteristic expansion properties of these alloys, namely, minimum coefficient of expansion, inflection temperature, and temperature range of the low coefficient were

tabulated. These data plotted against nickel content give the best coefficients of expansion and the temperature range over which they are available for alloys of any nickel content which contain the usual impurities. Both the coefficient of expansion and the inflection temperature rise with increasing nickel content above that of invar so that the zero coefficient obtainable with invar at ordinary temperatures is not available at higher temperatures.

The quantitative effect of manganese and silicon on the expansion of a 45 per cent nickel alloy was determined. The minimum coefficient of expansion was raised 0.26×10^{-6} (degrees Cent.) per per cent manganese, but was unaffected by one per cent silicon. The inflection temperature was lowered 20 degrees Cent. per per cent manganese and 30 degrees Cent. per per cent silicon.

Reducing the values of the minimum coefficient and inflection temperature to 0 per cent manganese and 0 per cent silicon on the basis of the foregoing data, the former was plotted against the latter. From the curve obtained the merit of a low-expansion alloy can be determined immediately from expansion data irrespective of its nickel content; that is to say, without recourse to chemical analysis.

Expansion tests of a commercial steel approximating invar composition as cold-worked and after annealing showed a reduction in coefficient of 1.5×10^{-6} (degrees Cent.) due to cold working, confirming a value previously reported. By this means a zero coefficient can easily be obtained provided the nickel content is near that of invar and the impurity content is low. Previous difficulty in obtaining a satisfactory coefficient with domestic invar compositions can be traced to the high content of impurities.

In conclusion the writer wishes to express his appreciation of the assistance and co-operation of R. H. Wynne, who is responsible for the chemical analyses given, of L. W. Schad, who made the check expansion tests, and of J. R. Gier, who made the synthetic alloys used. Appreciative acknowledgment is also due to P. H. Brace for his stimulating interest in the work, and to S. M. Kintner and the management of the Westinghouse Electric and Manufacturing Company for permission to publish the results.

DISCUSSION

F. B. FOLEY: Mr. Scott, what size specimens did you use in this experimental work and how long do you suppose it would take the specimen to come

to equilibrium condition as the temperature was increased from that of liquid air?

HOWARD SCOTT: We used a specimen a quarter inch in diameter and four inches long. It is not necessary to use a specimen of as large diameter as that.

The matter of errors due to temperature gradients in the specimen is covered in the paper. There is some error, of course, due to temperature gradients, but except at the start of cooling or heating, and particularly of cooling in liquid air it is negligible in comparison with the errors of measurement. The temperature is measured to perhaps plus or minus one degree Cent. and that is sufficient for the accuracy of the length measuring instrument used. The numerous possible sources of error are discussed at length in the paper.

H. C. KNERR: Some comments from Mr. Scott as to the possible explanation of these low coefficients of thermal expansion would be valued. It has been suggested that they are connected with the depressed transformation point.

HOWARD SCOTT: That is another point that is covered in the original paper. There has been only one explanation offered, so far as I know, of the low coefficient of expansion of these iron-nickel alloys, and that does not seem to hold water. I refer to that given in Professor Benedicks' recent book. He believes that the low expansion observed in invar is due to the expansion of one constituent from gamma to alpha while the other constituent contracts so that the net effect is zero or a small volume change. In other words, he believes that the structure is duplex and that there is a difference in composition, just as you find in meteorites, except that it is on a very much smaller scale.

The objection that you immediately find to this idea is that the transformation involved, the irreversible transformation, as was shown in the first slide, has an enormous hysteresis, amounting to hundreds of degrees between heating and cooling, whereas there is no hysteresis that you can detect in the low-expansion anomaly of invar.

There are several features of this anomaly, however, which are suggestive. For one thing, the inflection temperature corresponds to the Curie point, that is to the point at which the metal loses its magnetizability, which is known as the Curie point in iron and steel, or the A_2 point in iron. As a matter of fact, the point that I call the inflection temperature is called the A_2 in another paper before this session from Professor Honda. Identification by A_2 is objectionable because A_2 refers to iron. The magnetic transformation, however, is carried over from the nickel side of the diagram and is continuous with that found in pure nickel.

There is another rather suggestive effect in this connection. As you may know, Gruneisen discovered from theoretical considerations that the ratio of coefficient of expansion to the specific heat is a constant for a given metal and he has confirmed it experimentally. In other words, the coefficient of expansion is quite definitely tied up with the specific heat. Those of you who are familiar with theoretical physics are, however, probably aware that the specific heat effects are by no means easily accounted for. Hence the low coefficient of expansion of invar-type alloys remains an unsolved problem.

Educational Section

These Articles Have Been Selected Primarily For Their Educational And Informational Character As Distinguished From Reports Of Investigations And Research

FACTS AND PRINCIPLES CONCERNING STEEL AND HEAT TREATMENT—Part XVII[1]

Abstract

This is the second of a series of articles on the subject of case hardening. In this article it has been attemped to explain as simply as possible the mechanism of carburizing and the effect of the different heat treatments following carburizing. Some of the practical applications of the principles here described to the carburizing process will be taken up in a future article.

Some of the points covered in this article are as follows:—Carburizing is due to solution of carbon into steel from some carburizing gas. The gas may be generated by a solid or a liquid material. Temperature, pressure, volume, and concentration enter into a chemical equilibrium. Decarburizing may take place during carburizing. The effect of five different heat treatments after carburizing are described. The article is illustrated with numerous diagrams and photomicrographs.

The Carburizing Process

IN THE last article it was brought out that a steel suitable for case hardening should be low in carbon and might be either a plain carbon or an alloy steel. Such a steel will not harden appreciably when heated and quenched. Consequently the first step in the case hardening process consists in raising the carbon content of the outer layers of the steel high enough to enable the surface layers of the steel to harden when quenched from above the critical point. This operation of increasing the carbon content of the sur-

[1]This is the seventeenth installment of this series of articles by H. B. Knowlton. The several installments which have already appeared in Transactions are as follows: March, June and October, 1925; January, April, May, June, August, October, December, 1926; March, May, July, September, November, 1927; January, 1928.

The author, H. B. Knowlton, member of the Fort Wayne Group of the Society, is metallurgist of the Fort Wayne Works, International Harvester Company, Fort Wayne, Ind.

face layers is known as "case carburizing" or merely "carburizing." The high carbon layer produced near the surface of the steel is called the "case." In general it is usually attempted to produce a case with a maximum carbon content of 0.80 per cent or more.

General Classification of Carburizing Materials

The case is produced by heating the steel in contact with some material which will yield carbon to the steel. The material used for carburizing may be either a solid, a liquid or a gas. Among the solid carburizing materials may be mentioned charcoal, coke, leather, bone and various "compounds" usually containing one or more of the above materials mixed with certain chemicals. When this type of a carburizing material is used the steel to be carburized and the carburizing material are packed in pots or boxes or other suitable containers so that each piece of steel is completely surrounded by the carburizing material which is generally used in the form of small granules. These boxes are then heated to the carburizing temperature for a certain length of time.

The liquid carburizers include the cyanides, the ferrocyanides, cyanamid, and other similar chemicals or mixtures of chemicals. There are two general methods of using these chemicals. In the first method the cyanide (or other chemical) is heated in a pot to the desired temperature which is well above the melting point of the cyanide and the parts to be hardened are immersed in the melted cyanide until a case of the desired depth is formed. As a general rule the steel is quenched immediately on removal from the pot. This method is used primarily in the production of very thin cases. Sometimes when only a few pieces are to be treated the cyanide, in a powdered form, is sprinkled on the hot steel. This method is used particularly by blacksmiths. The steel is heated in a forge. When hot enough it is removed and the cyanide or other "tempering powder" is sprinkled on the steel. Generally the steel is returned to the forge and the operation repeated several times before the steel is finally quenched. As the powdered cyanide melts and adheres to the hot steel, this method is merely a variation of the method of heating the steel in melted cyanide.

In gas carburizing the steel is heated to the desired temperature in a closed retort and some gas such as carbon monoxide,

methane, "city gas," or natural gas is passed through the retort. Under the proper conditions the surface of the steel absorbs carbon from the gas. The results obtained depend upon the character of the steel, the composition of the gas, the temperature of the retort, the time of exposure and the volume and the pressure of the gas.

It may be interesting to note that while carburizing materials are usually divided into solids, liquids and gases as given above, that all case carburizing is probably gas carburizing. Efforts to carburize steel by heating it in contact with carbon particles in a vacuum or in an atmosphere of an inert gas have met with failure, at least so far as commercial carburizing is concerned. When an ordinary solid carburizer such as bone, leather, charcoal, coke or mixtures of one or more of these with chemicals is packed in a carburizing container there are always air spaces between the granules of the carburizing material. Consequently no matter how tightly the box is packed there is always some air included. When the box containing the carburizing material is heated there is a partial burning of the carburizing material until the air in the box is used up. As all of the solid carburizers mentioned contain carbon the product formed by the partial combustion or burning is carbon monoxide gas. It is really this gas which carburizes the steel. If the carburizing compound contains oil it may be well expected that the oil will become vaporized when the material is heated. This oil vapor may also have a carburizing action upon the steel. Organic materials in the compound may decompose to some extent under heat yielding carburizing gases. Finally most of the commercial compounds contain "chemical energizers" which decompose under heat and yield gases which directly or indirectly carburize the steel. Thus it will be seen that in all of these cases it is a gas which actually carburizes the steel. The carburizing materials and their action will be discussed in more detail later.

Effect of Temperature Upon Carburizing

One of the first essentials of the carburizing process is heat. In true carburizing, the carbon is dissolved by the surface layers of the steel. However, carbon does not seem to dissolve readily in steel unless the temperature is raised to above the lower critical point. At that point the solution of carbon takes place slowly and the amount of carbon which can be dissolved is comparatively small.

As the temperature is raised the speed of dissolving becomes greater and the per cent of carbon which can be dissolved becomes greater. The usual carburizing temperature in commercial practice is between 1600 and 1700 degrees Fahr.

The effect of the heating upon the steel may be best explained by selecting a single steel and describing the changes which take place as it is heated to different temperatures. Fig. 6 shows the

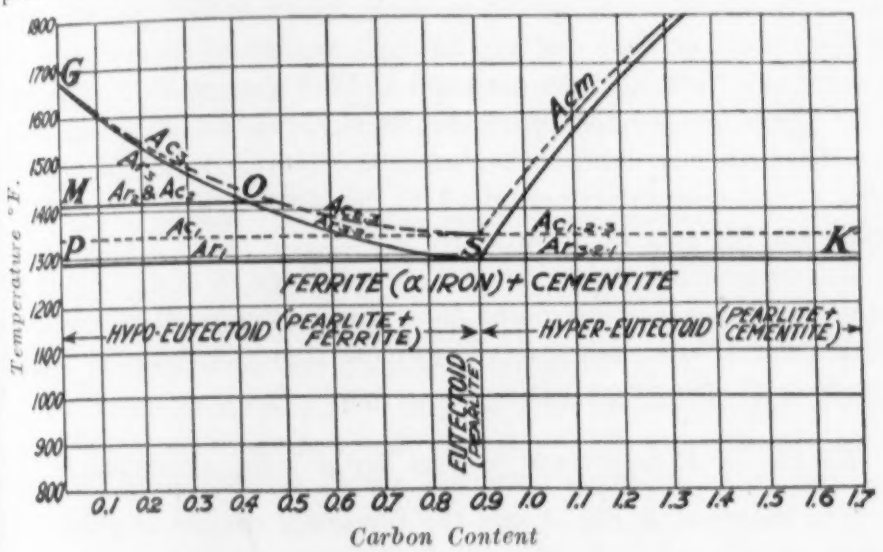


Fig. 1—A Portion of the Iron-Carbon Diagram Showing Critical Ranges for Plain Carbon Steels During Heating and Cooling.*

microstructure of a low carbon steel such as is used for carburizing. It is composed of ferrite (white areas) and pearlite (dark areas). As has been stated before the ferrite is carbonless iron while the pearlite is an alloy of iron and carbon containing about 0.85 per cent carbon. Fig. 1 shows the critical ranges for plain carbon steels on heating and cooling. When a steel as shown in Fig. 6 is heated to about 1330 degrees Fahr. it reaches the Ac_1 critical line. At this temperature the pearlite areas (which represent only about 23 per cent of the total composition of the steel) are changed into austenite or a state of solid solution. The ferrite is not affected. As the temperature is raised the austenite begins to dissolve the ferrite. When the Ac_3 line is reached (at a temperature of about 1500 degrees Fahr. for a 0.25 per cent carbon steel or about 1575 degrees Fahr. for a 0.10 per cent carbon steel) it is theoretically possible to dissolve all of the ferrite into the austenite. In other

*A portion of the iron-carbon diagram as published by F. B. Foley, *Fuels and Furnaces*, September, 1924, page 893.

words as the temperature is raised above the lower critical point the austenite is able to dissolve more and more ferrite.

In a similar way it is true that as the temperature is raised above the lower critical point, the austenite is capable of dissolving more and more carbon. The limit of the solubility of austenite for carbon is shown by the intersections of the Acm line with the temperature lines on the diagram. Thus the amount of carbon which may be dissolved in the austenite at the lower critical point is only 0.85 per cent, at 1500 degrees Fahr. it is about 1.10 per cent; at 1600 degrees Fahr., 1.2 per cent and at 1700 degrees Fahr., 1.25 per cent. These are the theoretical limits of solubility. This does not mean that when a plain carbon steel is carburized at 1700 degrees Fahr. it will necessarily contain 1.25 per cent carbon. In fact the carbon content may be lower.

In commercial carburizing it is customary to heat the steel to above the upper critical point thus transforming all of the steel into austenite, or in other words putting it into a condition which is capable of dissolving carbon.

Effect of Composition of the Steel Upon Carburizing

The diagram in Fig. 1 and the foregoing discussion applies to a plain carbon steel. In a general way the same principles apply to all of the alloy steels used for carburizing. The temperatures at which the critical points occur and the solubility of the austenite for carbon at different temperatures may be slightly different.

The composition of the steel also has an effect upon the speed of penetration of the carbon or in other words the depth of case which will be produced in a given length of time at a given temperature. In general it may be stated that alloying elements which combine with carbon are inclined to speed up the carburizing action while elements which do not combine with carbon retard the carburizing action. Thus chromium and manganese steels may carburize faster than plain carbon steels, while plain nickel steels carburize slower.

The Chemistry of Carburizing

Probably the most complete scientific investigation of carburizing was that conducted by Giolitti. In his book[2] he reviews all

[2]Cementation of Iron and Steel, Giolitti.

the previously published literature on the subject and describes numerous experiments of his own to determine exactly what happens during carburizing. It will be obviously impossible herein to give a complete summary of his work. It may be well, however to touch on some of the points brought out.

Carburizing with solid carburizers is nevertheless a form of gas carburizing. All solid carburizers such as charcoal, bone, leather, coke, etc., contain more or less carbon. When a box containing these materials is heated to a carburizing temperature there is a partial burning of the carburizing material to form carbon monoxide gas according to the following chemical equation.

$$\underset{\text{Carbon}}{C} + \underset{\text{Oxygen}}{O} \rightarrow \underset{\text{Carbon monoxide,}}{CO} \qquad \text{I}$$

If there were sufficient air in the carburizing box the carbon would burn to form carbon dioxide (CO_2) but since there is always an excess of carbon the gas formed is largely CO.

It seems probable that the carbon monoxide gas actually penetrates a short distance into the steel. The steel absorbs carbon from the gas according to the following equation.

$$\underset{\text{Carbon monoxide}}{2\,CO} \rightarrow \underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Carbon.}}{C} \qquad \text{II}$$

The carbon liberated by the above equation is yielded in such a fine form that it can be dissolved by the solid steel. (The finest carbon powder visible to the eye is much too course to dissolve into solid steel). The carbon dioxide produced by the reaction given in the above equation on coming into contact with the large amount of hot carbon particles in the carburizing box is again converted into carbon monoxide according to the following equation.

$$\underset{\text{Carbon dioxide}}{CO_2} + \underset{\text{Carbon}}{C} \rightarrow \underset{\text{Carbon monoxide}}{2\,CO} \qquad \text{III}$$

It will be noted that equation III is just the reverse of equation II. That is carbon monoxide and carbon may unite to form carbon dioxide or carbon dioxide may decompose to form carbon monoxide and carbon depending upon the conditions. This is what the chemist calls a reversible reaction and may be written as follows:

$$2\,CO \rightleftarrows CO_2 + C \qquad IV$$

The arrows pointing both directions signify that the reaction may go either direction depending upon the conditions. Both reactions are taking place during carburizing. When carbon monoxide comes in contact with steel containing very low carbon the gas gives up carbon to the steel according to equation II. When the CO_2 formed in this reaction comes into contact with the hot carbon of the carburizing compound the reaction follows equation III forming CO.

It will be seen therefore that during carburizing there is always both CO and CO_2 present in the carburizing box. The question may well be asked as to what effect the CO_2 gas has upon the steel which has been carburized. Under certain conditions the CO_2 gas may actually take carbon out of the steel to form more CO according to equation III. The taking of carbon out of the steel is called "decarburizing."

Thus there exists in the carburizing box a combination of gases which may cause either carburizing or decarburizing. The results obtained depend upon what the chemist calls "chemical equilibrium." When there is an excess of CO gas in the carburizing box the tendency is to carburize the steel until the carbon content of the surface of the steel reaches a certain point. After that the tendencies to carburize and decarburize are balanced, that is, they are in a state of chemical equilibrium. Thus when steel is heated in a carburizing mixture the carbon content at the surface of the steel is increased until it reaches a quantity which is in equilibrium with the gases in the carburizing box. After this point is reached, further heating at the same temperature will cause the carbon to penetrate deeper into the steel but will not increase the maximum carbon content at the surface.

The equilibrium between the carbon in the steel, the CO, the CO_2 and carbon in the carburizing compound is governed by the temperature, and the pressure of the gases. Furthermore Giolitti showed that the quantity of gas which comes into contact with the steel affects the concentration of carbon produced in the steel. Other things being equal an increase of either the pressure or the quantity of the carburizing gases will increase the depth of penetration and the per cent of carbon at the surface of the steel.

From the foregoing discussion it may be seen that the chem-

istry of carburizing is rather complex. It may be well to stress several points. The depth of penetration of the carbon into the steel and the per cent of carbon in the outer layers of the case depend upon the steel whether plain carbon or alloy, and upon the temperature and pressure and quantity of gases which come into contact with the steel. Lastly the carburizing action depends upon the nature of the gases. A condition which favors the production of a large amount of carbon monoxide in the carburizing box should favor carburizing. On the other hand a condition which favors the production of a considerable amount of carbon dioxide might even cause decarburizing. Sometimes decarburizing occurs at the end of a carburizing run due to the fact that air has leaked into the boxes. The excess of air at the top of the box favors burning of the CO gas to form CO_2. As already explained the CO_2 has a decarburizing action. This will be discussed more fully later.

This discussion has been limited to the action of CO and CO_2 gases. However these are not the only gases which will produce carburizing. Giolitti experimented with methane, ethylene and illuminating gas as well as with carbon monoxide. Compounds which contain oil yield hydrocarbon gases when heated. These also bring about carburizing.

It has already been mentioned that when cyanides or ferrocyanides are employed these chemicals decompose giving off gases containing both carbon and nitrogen. Probably none of these are absorbed by the steel. It is sometimes claimed that organic materials such as bone and leather decompose with heat yielding either nitrogen or cyanogen to the steel.

Diffusion of Carbon Into the Steel

It is a well known fact that the longer the steel is kept in contact with the carburizing material the deeper will be the "case" produced, that is, the added carbon gradually penetrates deeper and deeper into the steel. This may be due to a slow diffusion of the carburizing gases into the steel or to diffusion of the carbon dissolved in the surface layers. Probably both actions take place. In either case the highest carbon content would appear at the surface of the steel and there would be a gradual decrease in the carbon content from the surface of the steel to the bottom of the case or the beginning of the core.

The dissolving of carbon near the surface and the diffusion deeper into the steel may be compared with the dissolving of salt in water. Suppose, for example, that salt was gradually added to one end of a trough of water. Eventually the water at that end of the trough would become a concentrated brine solution. The concentration of salt in the water would gradually decrease from that end to the other end of the trough. In fact the water at the far end might not even taste salty. If the solution in the trough could be frozen suddenly it would form a solid cake of ice which would contain a large amount of salt at one end and no salt at the other end. No diffusion of the salt through the ice would be expected.

In a similar way carbon is added to steel during carburizing producing a concentration of carbon at the surface and a gradual decrease of carbon from the surface to the bottom of the case or the beginning of the core where the carbon is no higher than in the original steel. After the steel is cooled there is little or no diffusion of the carbon.

To carry the analogy a little further suppose that salt solution in the trough were allowed to stand for several days at ordinary temperatures. The salt would gradually diffuse through the water until finally there would be an equal concentration of salt in all parts of the tank, that is, the concentration of the salt would be decreased at one end of the tank and increased at the other end.

In a similar way if steel after being carburized is kept at a temperature above the critical point for several hours without further carburizing, there is a tendency for the concentration of the carbon at the surface while the carbon diffuses deeper into the steel.

The diffusion of the carbon already dissolved deeper into the steel has a practical application. When it is desired to produce a deep case without producing too high a carbon content at the surface, the following method is sometimes used. The steel is first carburized at a fairly high temperature (1700 degrees Fahr. for example) thus producing a case having a high carbon content at the surface. The temperature is then dropped to about 1500 degrees Fahr. and is held at that temperature. As this temperature does not favor as high a carbon content the result is that the carbon content in the surface layer is decreased and the carbon penetrates deeper into the steel.

Chemical Composition of the Solid Solution

In the foregoing it has been stated that the carbon dissolves in the austenite. Some authorities claim that the solid solution known as austenite is really a solution of iron and iron carbide. This assumes that the carbon first combines with a portion of the iron forming the chemical compound iron carbide or cementite and that it is this compound which dissolves in the austenite. Unfortunately the metallurgical microscope does not reveal whether the austenitic solution contains carbon or iron carbide. The X-ray method of testing, more recently developed, throws a little more light on the subject. Some of the experimenters with this method of testing claim that austenite is a solution of iron and carbon. This point is of interest more from a techincal than a practical standpoint. Consequently the present writer does not wish to enter into the discussion. For simplicity, austenite has been described herein as a solution of iron and carbon.

Effect of Slow Cooling Upon the Carburized Structure

The changes which take place during slow cooling from carburizing can be best explained by referring to the diagram showing the critical points on cooling (see Fig. 1). The upper curves of this diagram marked Ac are the critical points on heating this series of steels while the Ar or lower curves are the critical points on cooling.

The study of the changes taking place in the case of a carburized steel during slow cooling from the carburizing temperatures is rather complicated as the carbon content decreases from the surface to the core. For simplicity consider the outer zone of a case containing a maximum of 1.20 per cent carbon. Assuming that the carburizing temperature was 1700 degrees Fahr., there would be no change in the structure until the steel cooled to about 1550 degrees Fahr. or the Ar_{cm} point for a 1.20 per cent carbon steel. At that temperature the excess cementite would begin to separate out of the solid solution. As the temperature continued to fall from that temperature to the $Ar_{3\text{-}2\text{-}1}$ point (about 1280 degrees Fahr.) more and more of the excess cementite would separate out. If the cooling has been sufficiently slow all of the cementite will be separated out when the steel reaches the $Ar_{3\text{-}2\text{-}1}$ point. As the

temperature falls below this point the austenite is transformed into pearlite.

The cementite which separates out during slow cooling takes the form of envelops surrounding the original austenite grains. As the surface polished for microscopic examination is a cross section through the grains, cementite envelops appear in the photomicrograph in the form of a white network surrounding the grains (See Fig. 4). If it were possible to photograph the solid grains instead of a surface cut through them it would be seen that the cementite really exists in the form of very thin envelops completely surrounding each grain.

The formation of cementite crystals during slow cooling from the carburizing temperature follows the general laws of crystallization. During any slow crystallization there is a tendency for the crystals to grow by building on the first ones formed. Thus when a piece of carburized steel cools slowly, the first crystals of cementite are formed when the surface of the steel reaches the Ar_{cm} line. As the temperature continues to fall more cementite builds on the first crystals formed. Thus the envelops of cementite are built up extending inward from the surface. This means that there must be some migration of the carbon atoms through the austenite in the case to form the cementite crystals at the surface. Consequently during slow cooling there is a tendency for the carbon to concentrate near the surface.

On the other hand if the steel is quenched from the carburizing temperature, the cooling is too rapid to permit any migration of the carbon. As a result the carbon remains in the same position that it was during carburizing. In other words in a specimen which is quenched from the carburizing temperature there should be a gradual decrease in the carbon content from the surface of the steel to core.

This effect of the speed of cooling upon the carbon content in different parts of the case is shown clearly in Figs. 2 and 3. These were taken from Giolitti. They represent the results of carbon determinations at different depths below the surface of the steel. In both cases the specimens used were round bars. Fig. 2 shows the distribution of carbon in the specimen which was cooled slowly while Fig. 3 shows the gradual decrease in the carbon content in the specimen which was quenched. (It happens that the conditions

of carburizing of the two specimens were not exactly the same. Nevertheless these diagrams serve very well to illustrate the effect of the speed of cooling upon the distribution of carbon.)

The principles of crystallization of the cementite in the higher carbon zone of the case apply as well to the crystallization of the free ferrite in the lower carbon zone of the case which forms the gradation zone between the case and the core. For example con-

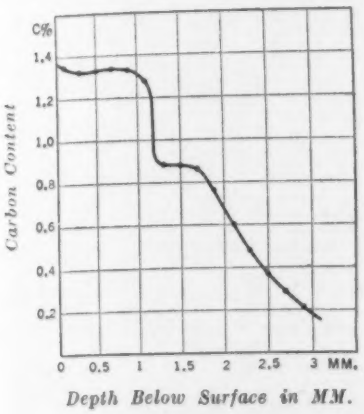


Fig. 2—Curve Showing Liquation of Carbon in Iron Due to Slow Cooling. (Giolitti.)

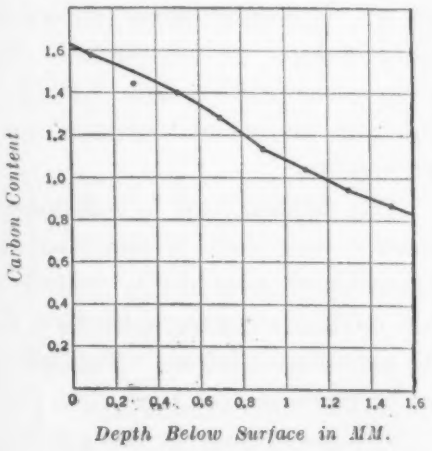


Fig. 3—Curve Showing Prevention of Liquation of Carbon in Iron by Quenching. (Giolitti.)

sider what happens when a steel which originally contained 0.20 per cent carbon is allowed to cool slowly from the carburizing temperature. The Ar_3 critical point of the core (0.20 per cent carbon steel) is reached at a temperature a little below 1500 degrees Fahr. (See diagram Fig. 1.) At this temperature the ferrite in the core begins to crystallize out. This action continues until the Ar_1 point is reached at a temperature of about 1280 degrees Fahr.

The deeper zones in the case contain less than 0.85 per cent carbon. Consequently as the temperature drops through the critical points for these zones there is a crystallization of free ferrite there also. This crystallization of free ferrite in the bottom zone of the case proceeds by building ferrite onto the crystals already formed in the core, producing networks of free ferrite extending out from the core into the case.

Consequently just as there is a tendency for the segregation of cementite in the outer zones of the case there is also a tendency for a segregation of free ferrite in the deepest zone in the case. This leaves a band through the center of the case which contains

neither free ferrite nor free cementite. Let it be said again that this segregation of free ferrite and free cementite is due to the process of gradual crystallization taking place during slow cooling from carburizing. The rapid cooling by quenching from carburizing does not allow sufficient time for this action to take place.

The microscopic structure of the three zones of the case of a piece slowly cooled from the carburizing temperature is shown in Fig. 4. The outer zone (shown at the top) is composed of pearlite and envelops of cementite. The metallographists call this the "hypereutectoid" zone, ("hypereutectoid" means more than eutectoid, in other words a steel containing more than 0.85 per cent carbon).

The central zone is composed entirely of pearlite. This is called the eutectoid zone. A composition which gives a structure entirely composed of pearlite is called an eutectoid composition. For a plain carbon steel the eutectoid composition is one containing about 0.85 per cent carbon. For alloy steels the eutectoid composition may be more or less than 0.85 per cent carbon.

The lower zone is the gradation zone between the case and the core. This is called the hypoeutectoid zone meaning that it is of less than eutectoid composition. In this zone the carbon content gradually decreases and consequently the quantity of free ferrite increases. It will be noted that it is difficult to draw a sharp line where the case leaves off and the core begins.

Effect of Shape of Piece Upon the Structure of the Case

What has been said concerning the concentration of cementite near the surface of a round bar during slow cooling applies to an even greater degree in the case of a square bar. A cross section cut through a square bar after carburizing and slow cooling will show that there is a greater concentration of carbon at the corners than there is along the sides of the square. This is due to the fact that the corners cool first, consequently the crystallization of the cementite during cooling starts at the corners before it does along the sides. The greatest concentration of all occurs at the corners of the bar. The same principle applies to other shapes. A greater concentration of cementite occurs at the corners and along the edges.

Effect of Carburizing Temperature Upon the Structure

It has already been stated that during slow cooling the

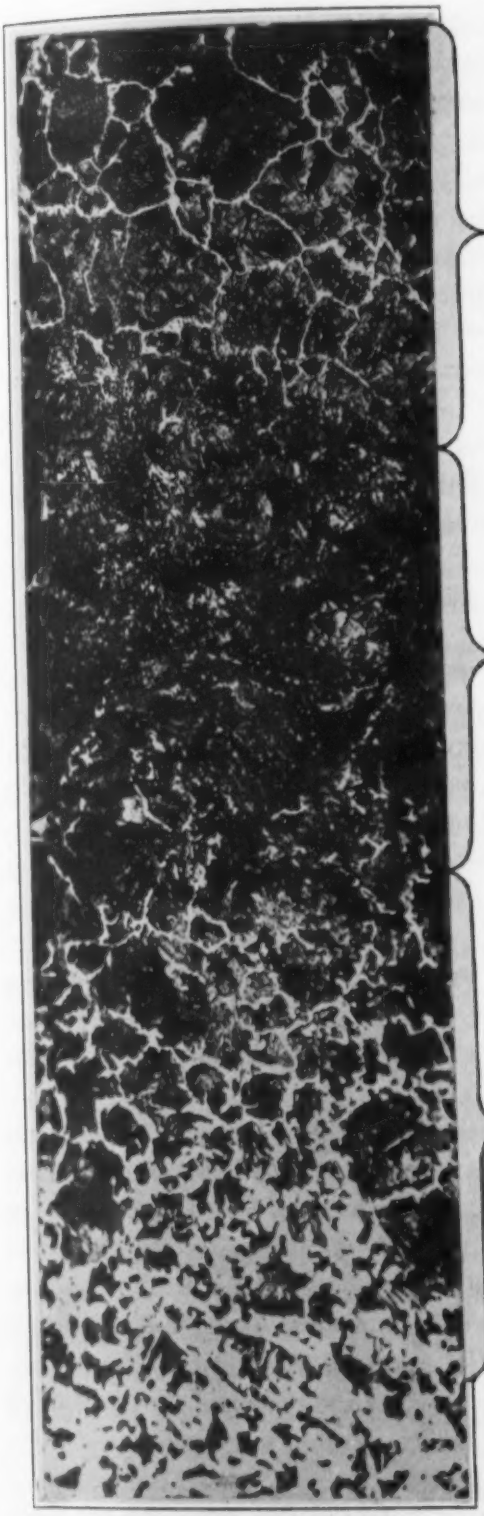

Surface of the Specimen
Hypereutectoid Zone
(Zone containing more than 0.85 per cent carbon)
Background is pearlite. The white network is cementite in the envelop form.
Eutectoid Zone
(Contains about 0.85 per cent carbon)
Structure is entirely pearlite.
Hypoeutectoid Zone
(Contains less than 0.85 per cent carbon but more carbon than that contained in the core)
Background is pearlite. White areas are free ferrite.
Core

Fig. 4—Photomicrograph Showing the Structure of the Different Zones of a Case After Carburizing and Slow Cooling. Mag. 125 x. (Guthrie.)

cementite tends to build out in envelops surrounding the austenite grains which are formed during heating. The size of these austenite grains depends upon the composition of the steel and the temperature to which it is heated. If a single steel is heated to different temperatures, it generally follows that the higher the temperature the larger will be the austenite grains formed and consequently the coarser the network of cementite formed during slow cooling. On the other hand some kinds of steel are more subject to grain growth than others. For example chromium-vanadium steel is not as likely to form coarse grains as is a plain carbon steel. Comparatively recently it has been brought out that steels which fall in the same general classification will not show the same amount of grain growth on heating. This will be discussed more in detail under normal and abnormal steels.

Best Carburized Case

There may be some difference of opinion as what is the ideal case. It is generally agreed, however, that a case should be gradual, that is there should be no sharp line of demarcation between the case and the core or between the different zones of the case. The structure of the case shown in the photomicrograph (Fig 4) may be described as "gradual." Sometimes there is a very sharp line of demarcation between the core and the gradation zone of the case. Such a case may be described as "sudden." Some carburizing materials are said to produce sudden cases. Bullens states that some carburizing materials which give gradual cases at comparatively low carburizing temperatures may give more sudden cases at higher temperatures.

The concentration of cementite in the hypereutectoid zone tends to produce a line of demarcation between the eutectoid and the hypereutectoid. The concentration of either ferrite or cementite producing sudden lines of demarcation is sometimes called "liquation." It must be remembered that while liquation may be due in part to the carburizing material and the temperature of carburizing it is also due to the crystallizing action taking place during slow cooling from carburizing. Liquation may be prevented by quenching from carburizing or by proper heat treatment after carburizing and slow cooling.

If a sharp line of demarcation between the case and the core,

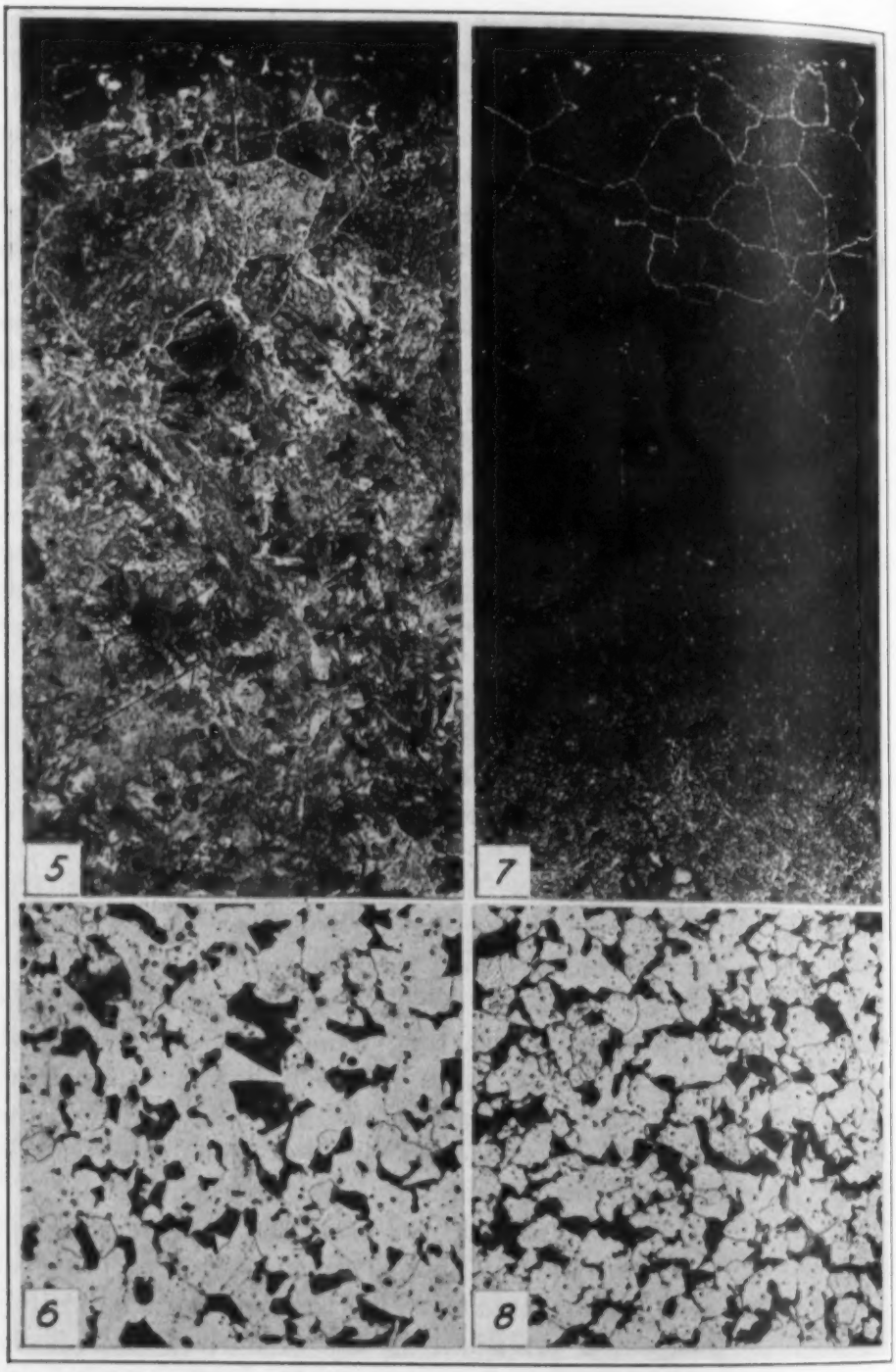
or between the different zones of the case remains after hardening, there may be danger of cracking between the zones where the line of demarcation occurs. One type of case hardening failure consists of just such a cracking, sometimes resulting in a peeling off of a portion of the case. This is described as "exfoliation."

A concentration of cementite at the surface particularly at thin edges or sharp corners is generally considered to cause a "skin brittleness." The spalling of such parts as ball races is sometimes said to be due to the segregation of free cementite in the outer zone of the case. Grinding cracks are sometimes attributed to the same cause.

For these reasons some metallurgists prefer to produce a case having a maximum carbon content of about 0.90 per cent. Needless to say there would be little or no free cementite in such a case. This may be justified in some instances. On the other hand a case containing only 0.90 per cent carbon maximum does not present as hard a wearing surface as one containing 1.20 per cent carbon at the outside.

If the brittleness is due to cementite it is probably due to the form in which the cementite appears rather than to the mere presence of cementite. If the cementite remains in the envelop form after hardening it may cause brittleness. Cementite is in itself a hard brittle material. If each grain in the outer zone of the case is completely surrounded by a thin envelop of cementite it should be expected that there might be danger of brittleness. However it is possible to give a heat treatment which will break up these envelops and put the cementite in a better form which does not cause so much brittleness. Quenching from carburizing will prevent the formation of the envelops in the first place. Furthermore not all of the spalling which occurs in service is due to the presence of envelops of cementite. There are other causes. This will be discussed later, under failures in case hardening.

It has already been stated that the grain size in the carburized slowly cooled condition depends upon the composition of the steel and the temperature of carburizing. It is very much doubted if it is possible to pick out a grain size in the carburized and slowly cooled condition which is ideal for all cases. It may be stated, however, that the grain size after hardening should not be excessively large. In general it may also be stated that it may be well to avoid high carburizing temperatures.



Figs. 5 to 14 are Photomicrographs Showing the Structures of the Case and the Core of Different Sections Cut from the Same Bar of 3115 Carburized Steel After Different Heat Treatments. Photomicrographs by F. C. Smith. All Magnifications 100 x. Fig. 5—Photomicrograph of the Case After Carburizing and Slow Cooling from Carburizing Temperature. Fig. 7—Photomicrograph of the Case After Carburizing and Slow Cooling, Reheated to 1350 Degrees Fahr. and Quenched in Water. Figs. 6 and 8—Photomicrographs of the Core of the Specimens Shown in Figs. 5 and 7.

Heat Treatment After Carburizing

Objectives

The following may be listed as the general objectives of the heat treatments following carburizing.

1. To produce a hard case
2. To produce a tough case
3. To produce a strong tough core
4. To relieve the strains caused by the quenching treatments.

Along with the objectives to be accomplished there may be listed two difficulties which it is sometimes necessary to avoid. These are:—

1. To avoid distortion
2. To avoid scaling.

It may not always be necessary to accomplish all of the objectives listed above. Some articles may require a hard case to resist wear but may not require any special treatment to strengthen and toughen the core. As an example of this case some set wrenches are husky enough in design that there is no danger of bending or breaking the wrenches no matter what heat treatment is given. The object of case hardening is purely to produce enough hardness to resist wear. Even toughness of the case may be unnecessary. On the other hand gear teeth require hardness and toughness in the case and strength and toughness in the core.

Similarly distortion and scaling are important in some instances and unimportant in others. Scaling and distortion must be kept at a minimum in the hardening of gears which are to receive little or no machining after hardening. In the case of shafts and bolts which are to be ground after hardening a moderate amount of scale and distortion may not be serious. Unfortunately the treatment which produces the best structure in the case and the core from a metallurgical standpoint may not produce the minimum distortion. The same is true with regard to heat treatments for the case and the core. The treatment which is the best for the case is usually not the best for the core and vice versa. It is generally necessary therefore to adopt a compromise treatment which most nearly fulfills all of the requirements.

Effect of Heat Treatment Upon the Case

As a carburized steel consists of a high carbon steel case and a low carbon steel core it may be well to consider the effect of heat treatment upon the case and the core separately. Assuming that a plain carbon steel has been carburized so as to produce a case containing a maximum of 1.20 per cent carbon, then the structure of the case after slow cooling should be similar to that shown in the photomicrograph Fig. 4. The outer zone would contain pearlite and envelops of cementite, the central zone pearlite and the inner zone pearlite and ferrite.

The effect of the heat treatment upon the three zones of the case may be worked out with the use of the diagram showing the critical points on heating (Fig 1). When the steel is heated the pearlite in the case is transformed into austenite as soon as the temperature passes the lower or $Ac_{3\text{-}2\text{-}1}$ critical point (about 1350 degrees Fahr.) The austenite grains formed just above the lower critical point are very small. When quenched in water the austenite is transformed into martensite. It would be expected therefore that if the steel were heated to just above the lower critical point and quenched the resulting case would be very fine-grained martensite. The fracture of a piece so treated shows a refined "silky" case.

On the other hand the cementite in the outer zone of the case is not affected by heating to just above the lower critical point. It remains in the envelop condition. This produces brittleness in the outer zone of the case and may produce spalling if the piece is subjected to certain kinds of wear.

The structure produced by heating to just above the lower critical point and quenching in water is shown in Fig. 7. (It happens that the steel shown is an alloy steel but the same principles apply to all of the carburizing steels.) The background is either martensite or troostite. The structure is too fine to show under low magnification. It will be noted that the network of cementite remains in the outer zone of the case after this treatment.

As the temperature is raised above the lower critical point the austenite grains grow larger. As a result the higher the quenching temperature the coarser will be the martensitic grains formed. Fig. 9 shows the case of the same piece after being quenched in water from 1450 degrees Fahr. The martensite in the background has become course enough to be barely visible at a magnification of

100 x. Some of the cementite has been dissolved but most of it remains. A fracture of this piece would show the case to be coarser than the one quenched from 1350 degrees Fahr. As the envelops of cementite are still present there would still be danger of surface brittleness. This case would probably test a little higher than the previous one but it would at the same time be more brittle, due to the coarser grain.

When the temperature is raised to above the Acm point (about 1620 degrees Fahr. for a plain carbon steel containing 1.20 per cent carbon) it should be possible to dissolve all of the excess cementite into the austenite. The rapid cooling of quenching even in oil prevents the cementite from separating out again. On the other hand heating to a temperature of 1600 degrees Fahr. produces a very coarse-grained austenite and consequently quenching from this temperature produces very coarse-grained martensite. Fig. 11 shows the structure produced by heating to 1600 degrees Fahr. and quenching in oil. It will be noted that the envelops of cementite have entirely disappeared. On the other hand the martensitic structure has become coarse enough to show the needles quite plainly even under the low magnification of 100 x. The fracture of the case after such a treatment would be very coarse. As might be expected, a case having such a coarse structure would be very brittle. The breaking up of the cementite envelops is an advantage but this is overbalanced by the coarsening of the grain. This treatment alone cannot be recommended for any part requiring any toughness in the case. However, this treatment followed by a low quench may be very valuable.

The customary double quenching treatment usually consists in heating to above the Acm point in order to dissolve all of the cementite, followed by quenching in oil, and then reheating to a temperature a little above the lower or $Ac_{3\text{-}2\text{-}1}$ point and quenching in water or oil. The second heating to just above the lower critical point produces a very fine-grained austenite. Quenching in water or oil from that temperature will produce very fine-grained martensite or troostite. The exact structure produced will depend upon the composition of the steel and the temperature and the speed of the quenching. In any event the structure will be fine if the quenching temperature is not too far above the lower critical point. The cementite which was dissolved during the first heating for the

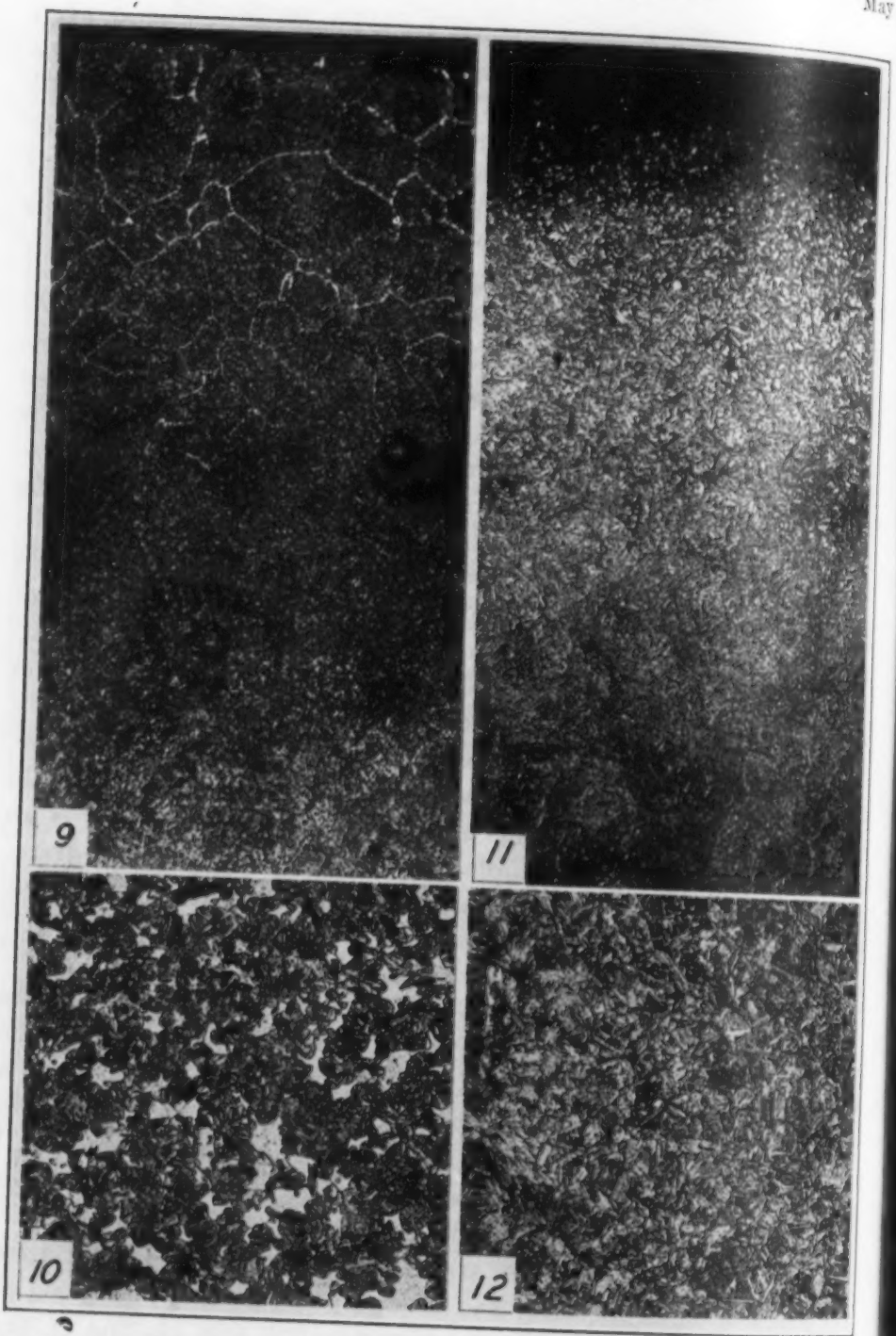


Fig. 9—Photomicrograph of Case, Carburized, Slowly Cooled, Reheated to 1450 Degrees Fahr. Quenched in Water. Fig. 10—Photomicrograph of the Core of the Same Specimen as Fig 9. Fig. 11—Photomicrograph of Case, Carburized, Slowly Cooled, Reheated to 1600 Degrees Fahr. Quenched in Oil. Fig. 12—Photomicrograph of the Core of the Same Specimen as Fig. 11.

high quench may precipitate out to some extent when the steel is heated for the second quench. If this does occur the cementite will be precipitated in the form of very fine dots which may increase the hardness but do not cause brittleness as does the presence of cementite in the form of envelops.

Fig. 13 shows the structure of the case after quenching from 1675 degrees Fahr. into oil followed by reheating to 1400 degrees Fahr. and quenching in oil. It will be noted that the structure is very fine and that there are no envelops of free cementite present. It may be that some of the very fine white dots near the upper edge of the picture are free cementite but they are too fine to be definitely indentified under the magnification shown. A fracture of this piece would show a very fine-grained silky case.

So far as the case alone is concerned this is probably the best heat treatment. Whether the last quench is in water or oil will depend upon the composition of the steel and the hardness to be obtained. In general the plain carbon steels should be quenched in water after the final heating but some of the alloy steels may be quenched in oil.

As a variation of this treatment the first or high quench may be given directly from the carburizing heat without allowing the steel to cool from the carburizing temperature before quenching. The second heating and quenching is the same as before. This treatment prevents the formation of cementite envelops in the first place. This has some advantages as it is certain to prevent the formation of envelops while reheating to what is thought to be the Acm point of the steel may in some instances fail to dissolve all of the cementite envelops formed during slow cooling from carburizing. There may be a higher concentration at edges and corners than is realized. Also the cementite in some of the alloy steels once formed is not always so easily dissolved.

On the other hand if it is desired to quench directly from the carburizing boxes it may be well to carburize at a comparatively low temperature (1600 degrees Fahr. for example). This means a slower carburizing process and probably a lower carbon content in the outer zone of the case. Quenching from high carburizing temperatures (1700 degrees Fahr. or above) may be accompanied by excessive distortion.

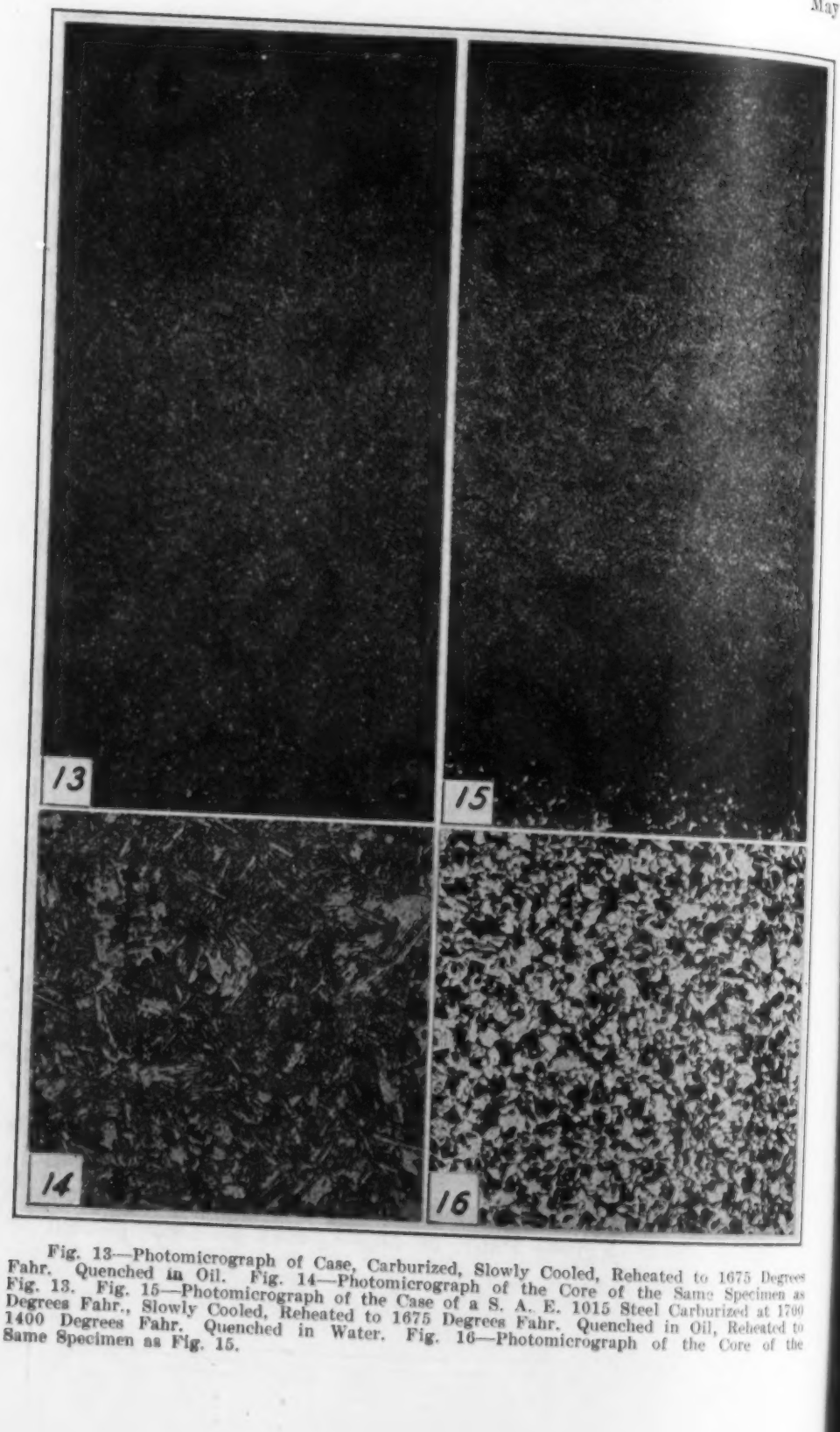


Fig. 13—Photomicrograph of Case, Carburized, Slowly Cooled, Reheated to 1675 Degrees Fahr. Quenched in Oil. Fig. 14—Photomicrograph of the Core of the Same Specimen as Fig. 13. Fig. 15—Photomicrograph of the Case of a S. A. E. 1015 Steel Carburized at 1700 Degrees Fahr., Slowly Cooled, Reheated to 1675 Degrees Fahr. Quenched in Oil, Reheated to 1400 Degrees Fahr. Quenched in Water. Fig. 16—Photomicrograph of the Core of the Same Specimen as Fig. 15.

Effect of Heat Treatment Upon the Core

The core of a carburized steel is essentially a low carbon steel, and responds to heat treatment the same as any other low carbon steel of the same composition which has not been carburized. It is usually stated that a plain carbon steel containing less than 0.25 per cent carbon cannot be greatly strengthened by heat treatment. On the other hand the tensile strength of the alloy case hardening steels containing 0.10-0.25 per cent carbon can be raised a great deal by heating to above the upper critical point of the steel and quenching. In general the low carbon steels whether plain carbon or alloy are fairly tough after quenching from above the upper critical point even without tempering. Tempering increases the toughness but lowers the tensile strength and the elastic limit (and the yield point) of these steels. Consequently the best treatment for producing strength in the core of a carburizing steel would probably consist in quenching from above the upper critical point followed by tempering at some temperature between 600 and 1100 degrees Fahr. depending upon the composition of the steel and the amount of strength and toughness to be produced. Obviously this treatment would not work out in the case hardening process. The high quenching temperature would produce a coarse-grained brittle case and the high temper would make the case soft, thus defeating the objectives of case hardening.

While it is usually impossible in case hardening to combine the ideal treatment for the case with the ideal treatment for the core, it is usually possible to adopt a compromise treatment which is at least fairly good for both. With some of the alloy steels it is possible to approach nearer to the ideal condition than it is with a plain carbon steel, or other alloy steels.

Exactly what happens to the core of a carburized steel during heat treatment may be best explained with reference to the diagram (Fig. 1) of the critical points on heating, and the photomicrographs.

Fig. 6 shows the structure of the core of a chromium-nickel carburizing steel as carburized and slowly cooled. It will be seen to consist of fairly coarse grains of ferrite (white) and pearlite (dark). When such a steel is heated to just above the lower critical point (intersection of the 0.20 per cent carbon line with the Ac_1 line in the diagram Fig. 1) the pearlite is transformed into austenite. At this temperature the ferrite is not affected. As the tem-

perature is raised the ferrite begins to dissolve into the austenite. When the steel is quenched only the portion which is converted into austenite is affected.

Fig. 8 shows the structure of the core after heating to 1350 degrees Fahr. and quenching in water. It will be seen that this structure differs very slightly from that of the core after slow cooling from the carburizing temperature. The dark areas are composed of a hardened constituent (probably troostite or sorbite). The per cent of dark areas are only slightly greater than in the slowly cooled core. The fracture of this piece would show a coarse-grained core. The physical properties of the core would not differ greatly from the one that was slowly cooled.

As the quenching temperature is raised more and more of the free ferrite is dissolved into the austenite and converted into a hardened structure by quenching. Fig. 10 shows the structure of the core after quenching in water from 1450 degrees Fahr. It will be noted that most of the free ferrite has been dissolved. The fracture of this core would be finer than the previous one.

Fig. 12 shows the structure of the core after quenching from 1600 degrees Fahr. which is well above the critical point of the core. It will be noted that there are none of the original ferrite crystals left after this treatment. A fracture of this piece would show the core to be more refined than those receiving the other heat treatments. Quenching from above the upper critical point also produces the maximum tensile strength in the core. Water quenching would produce a higher tensile strength than oil quenching but water quenching from such a high temperature might cause excessive distortion or cracking of the case. Plain carbon steels and some of the lower alloy steels are quite tough in the as-quenched condition. In any event the toughness can be increased by tempering after quenching although the strength is decreased at the same time. While the single high quench might be desirable so far as the core is concerned it is rarely the best case hardening treatment as it leaves the case in a coarse-grained brittle condition. It is claimed for at least one or two of the alloy case hardening steels that a moderately high quench may be used strengthening the core without greatly coarsening or embrittling the case. The quenching temperature employed is not as high as 1600 degrees Fahr.

Reheating a core which has been given a high quench to a tem-

perature just a little below the lower critical point (Ac_1 line Fig. 1) amounts to a high tempering operation. The hardened structure (martensite or troostite) produced by the high quench is gradually transformed into sorbite which is a structure having greater toughness but less strength. This is usually accompanied by a precipitation of some of the ferrite. However, the ferrite thus precipitated never takes the form of coarse grains that existed before the first quenching treatment. The high temper precipitates a great deal of free ferrite in the core of a plain carbon steel. In the core of some of the alloy steels much less ferrite is precipitated.

As the temperature is still further raised to a little above the lower critical point to give the refining quench for the case a small portion of the core is again transformed into austenite. When quenched, this small portion of the core is again hardened but the rest of the core remains in the condition produced by the high temper.

Fig. 14 shows the core of the chromium-nickel steel after quenching in oil from 1675 degrees Fahr. followed by reheating to 1400 degrees Fahr. and quenching in oil. Fig. 16 shows the structure of a plain carbon steel core after quenching in oil from 1675 degrees Fahr. followed by reheating to 1400 degrees Fahr. and quenching in water. It will be noted that the core of the alloy steel shows more of a heat treated structure than does the core of the plain carbon steel.

Effect of Different Treatments Upon Scaling and Distortion

Scaling is due to the action of air on hot steel. When steel is heated in an open furnace the amount of scale produced will depend upon the nature of the furnaces gases and the temperature and the time of heating. Other things being equal the higher the temperature and the longer the steel is kept at heat the greater will be the scaling action. In a fuel-fired furnace it is possible to keep the furnace atmosphere neutral or reducing in character and thus keep down the scaling since that action is a form of oxidation and is due to free air or oxygen in the furnace. It is also possible to reduce the amount of scaling by dipping the steel in hydrochloric acid, calcium chloride or copper sulphate solutions before heating. In an electric furnace there is always some air present. All that can be done is to keep the furnace as nearly sealed as possible pre-

venting a circulation of air through the furnace. When steel is heated in a lead pot it is protected from the action of the air while immersed in the lead. It only comes into contact with the air on being transferred from the pot to the quenching tank. When melted salt is used as the heating medium even this contact is avoided since some of the salt adheres to the steel when the steel is removed from the pot. When steel is quenched from the carburizing box there is only a little scaling as the contact with the air is limited to the time necessary to remove the steel from the box and transfer it to the oil tank. Assuming that the reheating is done in an open furnace it may be stated that heating for the high quench produces more scale than pot quenching or heating for the low quench. Similarly the two heats of the double quenching process causes more scaling than a single quenching treatment. It is doubted however if the amount of scale should be a determining factor in selecting the treatment to be given. If freedom from scale is of utmost importance a method of heating should be chosen which will not produce much scale.

Distortion, however, may be a very important factor in heat treating. Transmission and differential gears, for example, must be held quite accurately to size. Distortion is due to rapid or nonuniform heating or rapid or nonuniform cooling. During quenching the outside of piece cools faster than the center and the thin sections cool faster than the thick ones. These are among the factors that cause distortion. The faster the quench the greater is the difference in the speed of cooling between the outside and the center and the thin and the thick sections and consequently the greater is the danger of distortion. The speed of the quench depends upon the nature of the quenching medium and the difference in temperature between the piece being quenched and the quenching medium and some other factors. Water quenching is more rapid than oil quenching and quenching from a high temperature is more rapid than quenching from a lower temperature providing the quenching medium is the same in both cases. Consequently if it is necessary to keep down distortion it is desirable to keep down the quenching temperature and use oil for the quenching medium. Unfortunately this cannot always be done and produce the physical properties that are required.

It is usually necessary to quench plain carbon steel in water

for the final heat treatment in order to produce the required hardness. An alloy steel which will harden in oil or harden from a lower temperature than plain carbon steel has a decided advantage from the distortion standpoint. Also double quenching treatments are often necessary although there is a tendency in some quarters to increase the size of some parts so that they will be strong enough after a single quenching treatment or else to use an alloy steel which gives sufficiently high strength when given a single quenching treatment.

Before leaving the subject of distortion it should be remarked that the design of the piece plays an important rôle in distortion. Some designers seem to overlook this point entirely. In general the greater the difference in size between the thick and the thin sections and the sharper the angles involved the greater should be the distortion expected. Also it may be said that when gears are found not to be perfectly true when they reach assembly, the trouble does not always lie in the heat treating department. Some years ago when the writer was employed in a large gear plant he had several occasions to trace errors in gears. While there was usually a small amount of distortion produced in the heat treating department, it was usually found, the machining foremen's opinions to the contrary, that the largest portion of the errors in dimensions occurred in machining. Korp has brought out that the relation of the quenching temperature to the critical point is also a factor in determining the amount of distortion. This is an important point but it is not the only one involved in the problem of distortion. Lastly the distortion may be greater if the steel is not in a properly normalized or annealed condition when it reaches the heat treating department for case hardening. While this is important the idea is sometimes over worked. It is very much doubted if reannealing after machining reduces the amount of distortion produced in heat treating. The writer has several times had occasion to follow gears some of which were annealed both before and after machining while others were annealed before machining only. No difference in the amount of distortion produced by heat treating was observed.

Tempering After Hardening

All case hardened parts which require any strength or tough-

ness should be tempered after hardening to relieve the strains set up by quenching. The tempering temperature may be quite low as it usually it desired to relieve strains without decreasing the hardness of the surface. Case hardened plain carbon steel is quite noticeably softened by tempering at temperatures of 400 degrees Fahr. or above, particularly if the file is used for testing the hardness. The tempering temperatures usually recommended vary from 250 to 375 degrees Fahr. There may be some cases in which tempering temperatures as high as 500 to 600 degrees Fahr. are required. It should be remembered, however, that when brittleness is caused by poor quenching treatments, raising the tempering temperature is not the proper cure.

Standard Heat Treatments for Case Hardening

In the foregoing pages it has been attempted to explain the fundamental principles of carburizing and case hardening treatments, and to show the results that are produced in the case and the core by different treatments. It remains to summarize by discussing briefly the standard treatments which are usually recommended. In the following paragraphs it will be assumed that the steel used is a good carburizing grade of plain carbon or alloy steel and that the carburizing is performed by packing in boxes with a good solid carburizing material and that the depth of case and per cent of carbon in the case is proper for the part to be case hardened. The usual case hardening treatments may be divided into several classes as follows:—

I Single Direct Quench

Carburize at 1650 to 1700 degrees Fahr.
Quench in oil from carburizing box.
Temper 250 to 500 degrees Fahr.

This treatment is recommended only for plain carbon steel and only for parts which do not require strength and toughness. The case produced is coarse-grained and brittle. The structure of the core is good.

II Direct Quench Followed by Low Reheat and Quench

Carburize at 1600 to 1700 degrees Fahr.
Quench in oil from the carburizing box
Reheat above the lower critical point
Quench in water or oil
Temper at 250 to 500 degrees Fahr.

This treatment produces maximum hardness and grain refinement in the case. The formation of cementite envelops in the case is prevented by the direct quench from carburizing. The first quench is often too high to produce the maximum refinement and best physical properties in the core. This treatment may cause some distortion. The exact temperature for the second quench will depend upon the composition of the steel. For example the temperature recommended for a plain carbon steel is 1400 to 1450 degrees Fahr. while the temperature recommended for 3.5 per cent nickel steel is 1350 to 1400 degrees Fahr. Whether the last quench is in water or oil depends upon the composition of the steel and the hardness required. For any given steel the higher the final quench the coarser will be the case but the stronger will be the core.

III Direct Quench Followed by Two Reheating and Quenching Operations

Carburize at 1600 to 1700 degrees Fahr.
Quench in oil from the carburizing box.
Reheat to above the upper critical point for the core and the Acm point for the case.
Quench in oil
Reheat to above the lower critical point
Quench in oil or water
Temper at 250 to 500 degrees Fahr.

The only advantage of this treatment over Treatment II is that the steel is reheated after carburizing and quenching to a temperature which is nearer to the upper critical point for the core than is the carburizing temperature. For this reason this treatment produces more refinement of the core than does Treatment II. In other respects the treatment is the same as Treatment II. The temperature recommended for the second high quench varies from 1650 to 1700 degrees Fahr. for a plain carbon steel to 1500 to 1550 degrees Fahr. for a 3.5 per cent nickel steel. The last quench is from the same temperatures as given in Treatment II. As there are three quenching operations in this treatment more distortion may be expected following this than any other treatment.

IV Slow Cooling Followed by a Single Low Heat and Quench

Carburize at 1600 to 1700 degrees Fahr.
Cool in box.
Reheat to above the lower critical point
Quench in water or oil.
Temper at 250 to 500 degrees Fahr.

As this treatment involves only one quenching operation and that from a comparatively low temperature it should produce less distortion than any of the other treatments. If the quench is given from a temperature near the lower critical point the result will be refinement of the case but the core will be left very coarse. The envelops of cementite if present in the case will not be broken up by this treatment. If the quenching temperature is raised somewhat the core will be somewhat refined and strengthened but the case will become somewhat coarse-grained. This means a sacrifice of some of the toughness of the case.

It is claimed for one or two of the alloy steels that it is possible to produce good properties in both case and core by this single quenching treatment. For example, when 5 per cent nickel (S.A.E. 2512 steel) is used, some metallurgists recommend a single oil quench from a temperature of 1450 degrees Fahr. The last quench in a double quenching treatment is usually given as 1350 to 1400 degrees Fahr. The steel can actually be hardened at even lower temperatures as the nickel lowers the critical points. A quenching temperature of 1450 degrees Fahr. very nearly refines the grain of the core and produces a high figure for the tensile strength and the toughness of the core. At the same time this treatment does not coarsen the grain of the case the way a similar treatment would a plain carbon steel. So it is claimed that a single treatment will give good properties to both case and core. On the other hand 5 per cent nickel is one of the most expensive of all of the case hardening steels and its use is somewhat limited on that account.

V Slow Cooling Followed by Two Reheating and Quenching Treatments

Carburize at 1600 to 1700 degrees Fahr.
Cool in box.
Reheat to above the upper critical point for the core
Quench in oil
Reheat to above the lower critical point
Quench in oil or water.
Temper at 250 to 500 degrees Fahr.

This treatment is similar to Treatment III except that the steel is allowed to cool from the carburizing box instead of being quenched. It will produce slightly less distortion than that treatment. There may be danger of not dissolving all of the excess

Table Showing Recommended Case Hardening Treatments for Different Steels

Temperature in Degrees Fahr.

Treatment No.	Classification Specification No.	Plain Carbon 1015	3.5 Per Cent Nickel 2315	5 Per Cent Nickel 2512	Nickel-Chromium 3115	Nickel-Chromium 3215	Nickel-Chromium 3312	Nickel-Chromium 3415	Nickel-Molybdenum 4615	Chromium 5120	Chromium-Vanadium 6120
I	Carburize at	1650-1700									
	Quench from box				Not recommended for alloy carburizing steels						
II	Carburize at	1650-1700	1600-1650	.....	1625-1675	1625-1675	1600-1650	1600-1650	.....	1650-1700	1650-1700
	Quench from box										
	Reheat at	1400-1450	1350-1400	.....	1400-1450	1375-1425	1375-1425	1375-1425	.....	1425-1475	1425-1475
	Quench										
III	Carburize at	1650-1700	1600-1650	.....	1625-1675	1625-1675	1600-1650	1600-1650	.....	1650-1700	1650-1700
	Quench from box										
	Reheat at	1650-1700	1500-1550	.....	1525-1575	1525-1575	1475-1525	1500-1550	.....	1600-1650	1600-1650
	Quench										
	Reheat at	1400-1450	1350-1400	.....	1375-1425	1375-1425	1375-1425	1375-1425	.....	1425-1475	1425-1475
	Quench										
IV	Carburize at	1650-1700	1600-1650	1600-1650	1625-1675	1625-1675	1600-1650	1600-1625	1625-1675	1650-1700	1650-1700
	Cool in box										
	Reheat at	1400-1450	1375-1425	1400-1450	1400-1450	1375-1425	1400-1450	1400-1450	1475-1525	1525-1575	1525-1575
	Quench										
V	Carburize at	1650-1700	1600-1650	1600-1650	1625-1675	1625-1675	1600-1650	1600-1650	1625-1675	1650-1700	1650-1700
	Cool in box										
	Reheat at	1650-1700	1500-1550	1500-1550	1525-1575	1525-1575	1525-1575	1500-1550	1525-1575	1600-1650	1600-1650
	Quench										
	Reheat at	1400-1450	1350-1400	1350-1400	1375-1425	1375-1425	1375-1425	1375-1425	1375-1425	1425-1475	1425-1475
	Quench										

All temperatures given in degrees Fahr. Each of the above treatments should be followed by a temper at 250-500 degrees Fahr.

All the above data taken from the S. A. E. Handbook. Only S. A. E. steels are shown. For data on other carburizing steels consult the manufacturers. A steel of one carbon content only has been selected from each class. A variation of 0.05-0.10 per cent in the average carbon content does not greatly affect the heat treatment.

cementite if the first quench is not high enough. If properly carried out this treatment should give good results.

Quenching Temperatures for Different Steels

The foregoing are general heat treatments and are taken from the Handbook of the Society of Automotive Engineers. The writer has taken the liberty of expounding a little on the data given in the Handbook. For exact quenching temperatures for the different case hardening steels consult the preceding table.

Acknowledgment

The writer wishes to thank Messrs. R. G. Guthrie of the Peoples Gas Light and Coke Company and Fred C. Smith of the International Harvester Company for the excellent photomicrographs which they kindly loaned, for publication with this article.

Comment and Discussion

Papers and Articles Presented Before the Society and Published in Transactions Are Open to Comment and Discussion in This Column

DISCUSSION OF PAPER BY J. B. MUDGE AND F. E. COONEY ENTITLED, "EVALUATING QUALITY IN HEAT TREATED HIGH SPEED STEEL BY MEANS OF THE MILLING CUTTER"[1]

By G. C. Davis[2]

IN the paper by Messrs. Mudge and Cooney, the authors have not specified the treatment given in the salt bath, however, in the discussion, Mr. Mudge does make this clear. He indicates that simply one set of temperatures for heating, quenching and tempering were used and then arbitrarily assumed that because the results obtained were not as satisfactory that all tools treated by the bath method would not be as satisfactory as those treated in the atmosphere of an oven furnace. Now, assuming that he had tried other various combinations of heating, quenching and tempering temperatures with his bath and still obtained less satisfactory results, is it safe to assume that it is because the tool was heated in a bath instead of in an atmosphere that the results were less satisfactory? This writer maintains that not until he has tried every possible combination and found these results, is such a statement warranted.

In the first place, we have that old maxim that "heat is heat" and unless they are claiming that the gaseous heating medium and the bath medium actually enter into the composition of the steel or something like that, how do they account for such statements? What difference does it make whether the heat is applied by means of a gaseous medium or by a liquid medium? To my mind it is the old confusion of crediting the heating medium with some mysterious benefits. Actually if the steel were heated to the correct temperature and quenched and tempered correctly, the result would be the same.

In practice, there usually is a difference between the temperatures used in the bath method and in the oven method. Usually the bath temperatures used for the hardening heat are lower than the oven temperatures. This is not because of any mysterious effects from the different heating mediums on the steel but simply because of certain necessary procedures required by the different mediums. The difference is really due to the fact that in one case the surface is protected from oxidation while in the other case it is not.

[1] Mudge and Cooney, "Evaluating Quality in Heat Treated High Speed Steels by Means of the Milling Cutter," TRANSACTIONS, American Society for Steel Treating, Vol. XIII, February, 1928, page 221.

[2] The author of this discussion, G. C. Davis, is metallurgist with the Heat Treating Equipment Company, Boston.

Let us analyze that statement. The temperatures used for hardening high speed steel are so high that oxidation is very rapid and serious damage to the surface of the steel may result if certain precautions are not taken. As a piece of steel approaches the temperature of the furnace gases with which it is surrounded, the rate of heat penetration falls off very rapidly. If therefore, a piece of high speed teel is left in an oven furnace long enough to actually reach the same temperature as these gases, this would require such a long time that there would be very little of the steel left, since the oxidation is so rapid. Realizing that fact, we first preheat the steel as high as we can without serious oxidation or scaling. That is the primary reason for preheating high speed steel in hardening, which we all consider absolutely essential. Then what do we do? We plunge the steel into the oven furnace which is at a very high temperature and before the surface begins to sweat, pull it out and quench it. In other words, we preheat the steel as high as we can, we run our high temperature furnace at a higher temperature than desired and we thereby get the steel to some intermediate temperature before the surface is affected.

In a liquid heating medium we are protecting the steel from oxidation and surface effect. The result is that we no longer have that difficulty to contend with and we may then proceed to operate the bath temperature at the actual hardening temperature. In other words, with the bath protecting the surface of the work, we may leave it there long enough to actually reach the temperature as indicated by the pyrometer—the bath temperature. There are also a number of other features obtained from the use of a bath, such as the rapid rate of heating obtained, the uniformity of heating, etc., but the protection of the surface is the primary reason for using it.

To my mind the hardening of high speed steel in an open fire as is generally practiced today is a return to the crudest of heat treating for it is certainly a "hit and miss" method and since the pyrometer registers simply the furnace temperature, it is of little value. With a bath eliminating the danger of surface effect and making it possible to work to known temperatures and times, it is only necessary to do a little experimenting to find out what is the correct time and temperature and thus make it possible to duplicate results and obtain maximum performing tools every time.

Recently I had the pleasure of demonstrating this fact with one of the best tool makers in New England. This test was an actual work test and was carried out with such detail that it showed a reduction in the life of the high speed steel tool from overheating, which is a fact that I have always maintained is possible. It is difficult to get the co-operation of the user generally to show this, but in this instance such was the case.

The test was performed on a circular cutter similar to a milling cutter as discussed by Mr. Mudge. The tool was one that had offered the user a great deal of difficulty because the work performed was severe and the life obtained from their best tools was short. The following table lists the treatment given in the bath and the results:

Table I

Number of Hours Service Obtained From Milling Cutters Hardened by Means of a Salt Bath

	Temp. Deg. F.	Time Min.	Rockwell C	Temper Deg. F.	Time Hours	Rockwell C	Milled Hours
Test 1	2225	¾	65–66	1100	1	63	1
2	2225	¾	65–66	1050	1	62	1
3	2250	¾	65–66	1100	1	62	1½
4	2250	¾	65–66	1050	1	63	2¾
5	2250	1	64–66	1100	1	63	3
6	2260	½	64	1100	1	61	3
7	2270	½	65	1100	1	61	3
8	2280	1	64	1100	1	62	3
9	2300	½	64	1100	½	63	2½
10	2300	1	64	1100	½	63	2

The results of this test did not show any better maximum performance than the users best. However, as a result of this it was decided that 2260 degrees Fahr. for 1 minute was the correct hardening time and temperature. Fifty more of these cutters were therefore given this treatment with the usual temper and everyone of the fifty gave that best maximum performance which was only occasionally obtained by the user.

In closing, I would like to mention the factor of time at the high heat. In hardening high speed steel, we are endeavoring to get the greatest solution of the cementite globules but at the high temperature used we also have a tendency toward rapid grain growth. In my opinion the reason for the shorter life obtained in the above test at the high temperatures was due to grain growth. That is, I believe that there is a correct time and temperature for hardening high speed steel that will give the greatest solution of ingredients with the least possible grain growth and that the control necessary to accomplish this can only be obtained by the use of a bath.

Reviews of Recent Patents

By NELSON LITTELL, Patent Attorney
475 Fifth Ave., New York City—Member of A. S. S. T.

1,657,228, Method of Pickling Chromium-Iron Alloys, Louis Schulte, of Pittsburgh, Pennsylvania, Assignor to Allegheny Steel Company, of Brackenridge, Pennsylvania, A Corporation of Pennsylvania.

This patent relates to a method of pickling chromium alloys of rustless or stainless iron or steel which will effectively remove the scale from these alloys after annealing without attacking the sheet itself. To accomplish this result, the alloy is subjected to a preliminary pickling in hydrofluoric acid and is then rinsed and pickled by nitric acid for the removal of the scale. Instead of the use of hydrofluoric acid alone in the preliminary pickle, which has a tendency to pit the alloy, a metal or compound positive to both iron and chromium is added, such as potassium, sodium, calcium, or the like. A satisfactory preliminary pickle bath is formed by 1 to 6 per cent hydrofluoric acid and ½ to 3 per cent of nitre cake, which solution is used cold and the alloy immersed therein, after which the rinsing and nitric acid pickle follows.

1,662,158, Ferrous Alloy, Charles Meier, of Valparaiso, Indiana.

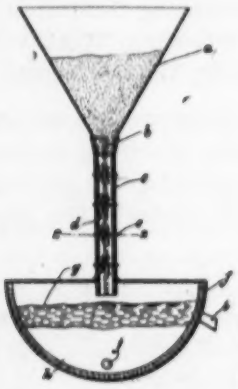
This patent describes a ferrous alloy, particularly intended for the production of iron castings in permanent steel molds, which will not form a scale of carbon adjacent the mold surfaces, is free flowing and does not form pin holes or voids in the finished product. The alloy comprises 2 to 4 per cent carbon, 2.5 per cent silicon, 60 per cent chromium, 1 to 3 per cent titanium, 0.5 to 1 per cent aluminum, 0.5 to 3 per cent manganese and 0.25 to 1 per cent phosphorus.

1,662,17, Method for Tempering Saw Blades, Plane Knives, and Similar Tools, Paul Hustadt and Karl Hustadt, of Remscheid-Hasten, Germany.

This patent describes a method of tempering saw blades, plane knives and the like, to remove warping and irregularities of shape, due to previous heat treatment. In a previous application, these inventors have described a method of hardening saw blades and the like by clamping them between heated plates and uniformly cooling the same. The present method is for the tempering of previously hardened tool blanks which may have been warped in the hardening process and consists of squeezing the blanks between electrically heated plates which are gradually tightened together to flatten out the irregularities, remove the warping and relieve any internal stresses. When the desired final temperature of the blank is reached, the entire area of both sides of the blank is instantaneously released from pressure and from contact with the heated plates and cooled in air or otherwise.

1,662,302, Manufacture of Steel and Alloys from Ironsand, Dirk Croese, of London, England.

This patent describes a method of manufacturing steel and alloys from titaniferous ironsand which it has heretofore been impossible to handle on a commercial scale because ironsand cannot be dealt with in a blast furnace and the use of an ordinary electric furnace is too expensive. In the drawing (a) indicates a hopper containing the sand and an outlet (b) which opens into a tubular electric furnace (c) having a suitable refrac-



tory lining (d) and several pairs of electrodes between which the ironsand must drop. The lower end of the furnace (c) opens into a crucible (f) heated in any suitable manner and provided with outlets (i) and (j) for tapping off the slag (g) or the metal (h) when desirable. The height of the furnace (c) is sufficient to ensure that the particles of ironsand are exposed to the electrodes (e) in passing there through for the length of time necessary to effect complete melting and reduction of the ironsand.

1,663,963, Magnesium Alloy and Method of Making Same, William R. Veazey, of Cleveland Heights, Ohio, Assignor to The Dow Chemical Company, of Midland, Michigan, A Corporation of Michigan.

This patent relates to a magnesium alloy and to a method of making the same in which the magnesium is alloyed with vanadium in amounts of several hundredths to several tenths of one per cent. Due to the difference in melting points, it is not feasible to heat the vanadium and magnesium together and the inventor prepares a vanadium pentoxide V_2O_5 and adds the same to the molten magnesium by pushing it below the surface so that the reaction between the magnesium and the vanadium pentoxide reduces the oxide to a metallic vanadium, which is incorporated in the molten magnesium to form the desired alloy.

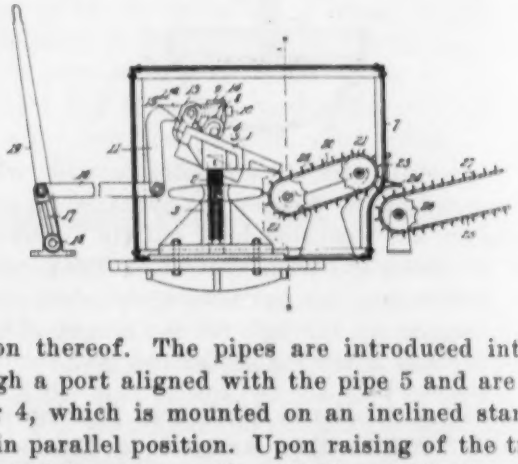
1,664,175, Heat Treatment of Alloys, Karl J. Jacobi, of Roselle, New Jersey, Assignor to Pacific Coast Borax Company, of New York, N. Y., A Corporation of Nevada.

This patent relates to the heat treatment of alloys by means of a fused salt bath of a borate which is substantially neutral in reaction. According to one example of the invention, a preheating bath and a separate tempering

or heat treatment bath may be used, the first consisting of calcium bi-borate CaB_4O_7 to bring the temperature of the tools up to about 1800 degrees Fahr. and in the main bath to maintain the temperature around 2250 degrees Fahr. The calcium borate remains on the tool in the form of a thin film. When removed from the bath, it is desirable to dip the tools into a cooling bath containing sodium carbonate at about 1000 degrees Fahr., which removes the film of calcium borate and at the same time cools the tools to the temperature of the cooling bath.

1,663,497, Method of Preventing Oxidation of Metal Pipe While Cooling, Benjamin P. Hazeltine, of Wheeling, West Virginia, Assignor to Wheeling Steel Corporation, of Wheeling, West Virginia, A Corporation of Delaware.

This patent describes an apparatus and method of handling a metal pipe to prevent oxidation thereof during cooling following its manufacture. The method and apparatus consists of a cooling chamber 7 adapted to confine a cooling medium which protects the pipes during their cooling and



prevents oxidation thereof. The pipes are introduced into the chamber 7 lengthwise through a port aligned with the pipe 5 and are received beneath a trough member 4, which is mounted on an inclined stand 1 and adapted to hold the pipe in parallel position. Upon raising of the trough 4 by means of the lever 19 and linkage connection 15, 16 and 17, the pipe 5 is permitted to roll down the incline 1 and fall between the posts 22 of the conveyor 20, where it is conveyed at a suitable rate toward the exit door 23 and passes out of the chamber. The apparatus thus protects the heated pipes after the completion of their manufacture until cooled below the point at which oxidation occurs.

1,665,146, Process of Making Commercially Pure Iron Alloys, Leo F. Reinartz and John H. Nead, of Middletown, Ohio, Assignors to The American Rolling Mill Company, of Middletown, Ohio, A Corporation of Ohio.

This patent describes a process of making commercially pure iron alloys of low carbon content, particularly for the production of a low carbon base alloy which can be used either as a pure iron or as an ingredient for chromium or other alloys. In the practice of the process molten commercially pure iron is poured into an electric furnace preheated to a high temperature, a reducing slag is made on the bath and the metal is thoroughly deoxidized or "killed" and to the "killed" bath, a low carbon chromium or ferro

chromium is added in amounts necessary to give the desired chromium content. By deoxidizing or "killing" the bath and utilizing a reducing slag, the loss of chromium is greatly reduced.

1,665,465, **Preparation for Cleaning Metal Preparatory to Painting, James D. Klinger and Clete L. Boyle, of Detroit, Michigan.**

This patent describes a preparation for removing rust, oxides, dirt, oils and greases from metals which can be easily rinsed from the metal leaving a clean surface. The compound consists of an admixture of phosphoric acid and ethyl methyl ketone in proportions of 25 per cent phosphoric acid, 40 per cent ethyl methyl ketone and 35 per cent water.

1,647,787, **Electric Induction Furnace. Jose Ricardo De Zubiria, Bilbao, Spain.**

In this electric induction furnace, a straight tubular channel is interchangeably connected to an opening in the wall of the hearth. The hearth can be adjusted relatively to and forced against the channel. A transformer core surrounds this channel, the primary winding being on this core.

1,648,707, **Induction Furnace. James M. Weed, Scotia, N. Y., assignor to General Electric Company.**

This induction furnace comprises a crucible providing a reservoir for the charge and a looped chamber communicating with this reservoir within which a portion of the charge constitutes a closed secondary. Means are provided for causing the charge to flow in a substantially spiral path through the chamber, the return flow being through the reservoir.

1,658,467, **Hardened Cast Iron, Karl Sipp, of Mannheim, Germany, Assignor, By Mesne Assignments, to Heinrich Lanz, Aktiengesellschaft, of Mannheim, Baden, Germany, a Corporation of Germany.**

This patent relates to the process of hardening cast iron to a high degree of uniformity, so that chisels and cutting tools for turning, planing and cutting lathes can be made therefrom and used with excellent results. In the previous patents, Nos. 1,502,983, 1,544,562 and 1,564,284 the process has been described for the production of cast iron possessing essentially the pearlite structure of eutectoid steel, with the graphite of cast iron showing only in small amounts finely divided and uniformly distributed. Tools are forged from these pearlite bars and then hardened by reheating and quenching in the same way as steel, the degree of toughness or hardness depending upon the temperature of the final reheating and cooling step. The hardness of the cutting edge of the cast iron tool is scarcely distinguishable from that of hardened normal tool steel. The new product is produced from a hardened gray cast iron having, for example, a carbon content of 2.9 per cent, 0.8 per cent silicon, 0.04 per cent sulphur, 0.6 per cent manganese and 0.1 per cent phosphorus. According to the inventor's statement, this invention opens up a vast new field for the use of cast iron.

THE ENGINEERING INDEX

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Arrangements have been made with The American Society of Mechanical Engineers whereby the American Society for Steel Treating will be furnished each month with a specially prepared section of The Engineering Index. It is to include items descriptive of articles appearing in the current issues of the world's engineering and scientific press of particular interest to members of the American Society for Steel Treating. These items will be selected from the copy prepared for the annual volume of the Index published by the A. S. M. E.

In the preparation of the Index by the staff of the A. S. M. E. some 1,200 domestic and foreign technical publications received by the Engineering Societies Library (New York) are regularly searched for articles giving the results of the world's most recent engineering and scientific research, thought, and experience. From this wealth of material the A. S. S. T. will be supplied with a selective index to those articles which deal particularly with steel treating and related subjects.

Photostatic copies (white printing on a black background) of any of the articles listed may be secured through the A. S. S. T. The price of each print, up to 11 by 14 inches in size, is 25 cents. Remittances should accompany orders. A separate print is required for each page of the larger periodicals, but whenever possible two pages will be photographed together on the same print. When ordering prints, identify the article by quoting from the Index item: (1) Title of article; (2) name of periodical in which it appeared; (3) volume, number, and date of publication of periodical; and (4) page numbers.

AIR HEATERS

INDUSTRIAL FURNACES. Metal Air Heater for Industrial Furnaces, W. Dyrssen. *Iron and Steel Engr.*, vol. 5, no. 2, Feb. 1928, pp. 81-88, 12 figs.

Methods in use for heating combustion air in metallurgical furnaces; heaters constructed so to withstand extreme temperature peaks that may occur; fundamental points in construction and operation of metal air heaters; Calco recuperator; Duraloy recuperator; Mantle recuperators; Blaw-Knox regenerative air heater.

ALLOYS

AGE HARDENING. Age-Hardening of Alloys, Hay. *Foundry Trade Jl. (Lond.)*. vol. 38, no. 602, Mar. 1, 1928, pp. 147-148.

Review and some new observations; age hardening was first observed in marked form in duralumin and discovered about 1902 by Wilm in Germany; term literally means hardening with age or time; application of age hardening of alloys to obtain best mechanical properties is now quite general practice. Abstract of paper read at Glasgow Branch of Inst. Metals.

EQUILIBRIUM DIAGRAMS. Equilibrium Diagrams, W. Rosenhain. *Foundry Trade Jl. (Lond.)*, vol. 38, no. 603, Mar. 8, 1928, pp. 169-173.

Explanation of equilibrium diagrams; simple and duplex alloys; nature of micro-constituents; transitional phases; maintaining condition of balance between solid and liquid; principle of phase rule; energy potential and metastable alloys; thermal analysis; dilatometry; alloying and its results; age hardening; equilibrium and future developments. Presidential address to Inst. of Metals. See also Metal Industry (Lond.), vol. 32, nos. 10 and 11, Mar. 9 and 16, 1928, pp. 259-261 and 275-277.

EQUILIBRIUM DIAGRAMS. The Equilibrium Diagram, W. Rosenhain. *Engineer (Lond.)*, vol. 145, no. 3765, Mar. 9, 1928, pp. 260-262, 2 figs.

Discusses points in connection with equilibrium states and their importance in understanding behavior of alloys; explains principle known as "phase rule" and kind of reasoning on which it is based; accuracy required in determination of equilibrium diagrams. Abstract of Presidential address to Inst. of Metals, March 7th.

HEAT RESISTING. Heat Resisting Alloys, T. H. Turner. *Metal Industry (Lond.)*, vol. 32, no. 6, Feb. 10, 1928, pp. 153-155, 4 figs.

Properties required in heat-resisting alloys; how demand for resistance to high temperatures has been met; main groups of heat-resisting alloys; choice of particular alloy; alloys for steam use. Abridged report of lecture given before Co-ordinated Societies in Birmingham, Eng. (To be concluded.)

Heat Resisting Alloys, T. H. Turner. *Metal Industry (Lond.)*, vol. 32, no. 7, Feb. 17, 1928, pp. 179-181, 3 figs.

Heat-resisting alloys in furnace work, and in connection with electricity, in internal-combustion engines, guns and rifles, for hot forging dies and in chemical industries. (Conclusion.)

ALLOYS, CAST

SHRINKAGE. Minute Shrinkage Cavities in Some Cast Alloys of Heterogeneous Structure, W. A. Cowan. *Inst. of Metals—advance paper*, no. 451, for mtg., Mar. 8-9, 1928, 6 pp., 7 figs.

Those members who are making a practice of clipping items for filing in their own filing system may obtain extra copies of the Engineering Index pages gratis by addressing their request to the society headquarters, whereby their names will be placed on a mailing list to receive extra copies regularly.

Cavities in certain heterogeneous alloys are described as due to shrinkage, accompanying change in volume between liquid and solid phases, of relatively low freezing-point component, where it last freezes after bulk of alloy has solidified at higher temperature; tin-base alloys are shown to contain minute shrinkage cavities when small percentages of lead are present, but to be practically free from similar cavities with no lead content.

ALLOY STEELS

Alloy Steels, Their Manufacture, Properties and Uses, H. C. H. Carpenter. *Royal Soc. of Arts—Jl.*, vol. 76, no. 3926, Feb. 17, 1928. pp. 326-351, 27 figs.

Fourth Cantor lecture dealing with silicon steels, chromium-vanadium steels; tungsten-chromium-vanadium steels, heat-resisting steels; gives tables on effect of oxygen, effect of steam, effect of carbon dioxide and effect of sulphur dioxide on steels and other alloys at various high temperatures; includes diagrams and photomicrographs.

HEAT RESISTING. Discussion of Roger Sutton's Paper "A study of Some of the Causes of Failure in Heat Resisting Alloys," D. Evans. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 493-494.

Discussion of paper published in Aug. 1927 issue of Transactions; points out that it is physical characteristics which determine value of article in actual use, and these characteristics can be most certainly secured from foundry which has had experience in foundry business before they attempt to make alloy steels.

STANDARDS. New List of Standards. *Iron Age*, vol. 121, no. 11, Mar. 15, 1928, p. 732.

Samples of steels and alloys now available from Bureau of Standards; table showing sample number, name, constituents, determined or intended use, weight of sample in grams, and fee per sample; detailed certificates of analyses are sent under separate cover to same destination as samples.

ALUMINUM

EXTRACTION. Basic Materials in the Extraction of Aluminum (Les produits de départ pour l'extraction de l'aluminium), G. Faessler. *Can. Chem. and Met.*, vol. 12, no. 2, Feb. 1928, pp. 35-39.

Résumé of basic materials and ores from which aluminum is produced; location of bauxite deposits; search for new materials containing aluminum, clay containing aluminum and location of deposits of feldspars in Canada.

PROPERTIES. Light Metals and Alloys—Aluminum, Magnesium. *U. S. Bur. Standards—Circular*, no. 346, Dec. 12, 1927, 397 pp., 115 figs.

Physical and mechanical properties of aluminum and magnesium and their light alloys, and variation in properties caused by changing composition of alloy, by presence of impurities, mechanical working, changes in conditions of manufacturing operations, and by heat treatment; selection of data available has been made and data checked by representatives of light-alloy industries; equilibrium diagrams for important alloy systems; protection against corrosion. Bibliography.

ALUMINUM ALLOYS

ALUDUR. New Hard Aluminum Alloy. *Metal Industry*, (*N. Y.*), vol. 26, no. 3, Mar. 1928, p. 136.

Aludur, developed by Société Anonyme pour l'industrie des Métaux, Lausanne; it is a special 98-99 per cent aluminum, hardened by a special process; resistance to corrosion, availability in all forms and easy machinability are claims made.

CONDUCTIVITY. The Thermal and Electrical Conductivity of Some Aluminium Alloys and Bronzes, E. Griffiths and F. H. Schofield. *Engineering* (*Lond.*), vol. 125, no. 3243, Mar. 9, 1928, pp. 301-303, 3 figs.

Investigation to obtain approximate values for thermal conductivities of alloys employed in construction of airplane engines; measurement of electrical conductivity of alloys has been undertaken merely to throw light on its relation to thermal conductivity. Paper read before Inst. of Metals.

CONDUCTIVITY. The Thermal and Electrical Conductivity of some Aluminum Alloys and Bronzes, E. Griffiths and F. H. Schofield. *Inst. of Metals—advance paper*, no. 457, for mtg., Mar. 7-8, 1928, 36 pp., 9 figs.

Two groups of alloys were investigated: (1) those rich in aluminum, with nickel, magnesium, iron, zinc, manganese, or silver as second or third constituents; (2) those rich in copper, with tin, zinc, lead, manganese, or aluminum; aluminum alloys were found to possess thermal conductivity of 70-80 per cent that of pure aluminum, while bronzes range from one-fifth to one-tenth of value for copper.

EGALITE. Specially Processed Aluminum Alloy Marketed as "Égalite," P. M. Heldt. *Automotive Industries*, vol. 58, no. 10, Mar. 10, 1928, pp. 416-417.

Alloy has been subjected to special process while in molten state; process said to give greater degree of uniformity of molecular structure and to increase tensile strength and elongation; process applicable to wide variety of compositions; recommended for casting cylinder heads; reduces maximum temperature; results of tests on engines with cast-iron and Egalite metal heads; effect of process explained.

PROPERTIES. The Constitution of Alloys of Aluminium with Silicon and Iron, A. G. C. Gwyer and H. W. L. Phillips. *Engineering*, vol. 125, no. 3239, Feb. 10, 1928, pp. 179-182, 9 figs.

Investigates conditions and limits of composition determining appearance of various constituents, with view to elucidating any structural changes taking place during ordinary operations of working and annealing. Paper read before Inst. of Metals. Abridged. (To be continued.)

PROPERTIES. The Constitution of Alloys of Aluminium with Silicon and Iron, A. G. C. Gwyer and H. W. L. Phillips. *Engineering*, vol. 125, no. 3240, Feb. 17, 1928, pp. 210-212, 12 figs.

Binary system iron-silicon; liquidus surface; notes on constituents; equilibrium conditions; aluminum corner of model; includes diagrams and photomicrographs. (Conclusion.)

PROPERTIES. Differentiation of Aluminum Alloys Based on the Use of pH Indicators (Méthode de differenciation des alliages d'aluminium basée sur l'emploi des indicateurs du pH), C. Quillard. *Académie des Sciences—Comptes Rendus* (*Paris*), vol. 185, no. 23, Dec. 5, 1927, pp. 1281-1283.

Properties of aluminum alloys may be

studied from consideration of colorimetric change in pH value of twice distilled water, or of solution of pure sodium chloride; American aluminum is attacked more than ordinary French product; cleaning by ether and sand blast increased attackability by water of both pure and industrial aluminum, but not always that of their alloys.

ALUMINUM BRONZE

Aluminium Bronze. *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 21-22.

Deals with color; corrosion resistance; machinability; compositions, melting and fluxes; influence of iron.

CASTING. Casting large Bronze Ingots, J. Strauss. *Metal Industry (Lond.)*, vol. 32, no. 6, Feb. 10, 1928, pp. 160-162.

Commercial ingots of aluminum bronze generally weigh 200 to 500 lb., according to dimensions of bars or sheets required; how they are melted and poured; methods of machining and forging; effect of forging and annealing temperatures on physical properties of aluminum bronze; properties of ingots. Abstracted from Iron Age, Dec. 8, 1927. (To be concluded.)

CASTING. Casting large Bronze Ingots, J. Strauss. *Metal Industry (Lond.)*, vol. 32, no. 7, Feb. 17, 1928, pp. 181-182.

Microstructure parallels macrostructure; function of dissolved gases; properties of forgings; increased hardness on heat treatment. (Conclusion.)

ALUMINUM-BERYLLIUM ALLOYS

Aluminum-Beryllium Alloys, R. S. Archer and W. L. Fink. *Am. Inst. Min. and Met. Engrs.—Tech. Pub.*, no. 91, Mar. 1928, 27 pp., 12 figs.

Production of beryllium by electrolysis from fluoride bath has developed to stage where it could be used commercially if there were sufficient demand for element; claims made in certain newspapers and technical articles in regard to strength and corrosion resistance of aluminum-beryllium alloys are not justified by experimental results; in present work emphasis is placed on beryllium alloys of low beryllium content.

ALUMINUM-COPPER ALLOYS

Aluminum- Copper Alloys (Causes de la variation de volume accompagnant le durcissement des alliages legers aluminium-cuivre), P. Chevenard and A. Portevin. *Académie des Sciences—Comptes Rendus (Paris)*, vol. 186, no. 3, Jan. 16, 1928, pp. 144-146, 1 fig.

Explains cause of volume change which first accompanies hardening of light Al-Cu alloys; volume change which occurs above 170 deg. in hardening process is due to some reaction, not yet known with certainty but most probably not analogous with martensite state in steels.

ANTI-CORROSIVE ALLOYS

Corrosion and Corrosion Resistant Alloys. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, pp. 167-171.

Describes processes of attack by gases and liquids and composition of various alloyed steels and non-ferrous metals for resisting destruction; surface films; most important external factor causing corrosion is presence of electrolytes in solution; iron-chromium alloys; chromium-nickel-iron alloys; non-ferrous alloys; choice of alloy. Reprint from Mech. World.

AUTOMOBILES

BODIES, STEEL. Sheet Steel For Automobile Bodies. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, pp. 157-162, 1 fig.

Detailed non-technical discussion of importance of and processes involved in manufacture of automobile-body sheet steels; cooperation of maker and user of sheets; importance of making own bar stock; open-hearth charge. (To be continued.)

BODIES, STEEL. Sheet Steel for Automobile Bodies. *Blast Furnace and Steel Plant*, vol. 16, no. 2, Feb. 1928, pp. 245-248.

Detailed non-technical discussion of importance of and processes involved in manufacture of automobile-body steels. (To be continued.)

AUTOMOBILE PLANTS

HEAT TREATING DEPARTMENT. Modernized Heat Treating Equipment, F. W. Manker. *Gas Age-Rec.*, vol. 61. no. 6, Feb. 11, 1928, pp. 182-184, 4 figs.

In designing and equipping its new forge shop and heat-treating department, Willys-Overland Co. paid special attention to heating operations; as result it has today one of the most up-to-date and modern forging and heat-treating plants in the world.

BRONZE

CONDUCTIVITY. The Thermal and Electrical Conductivity of some Aluminium Alloys and Bronzes, E. Griffiths and F. H. Schofield. *Inst. of Metals—advance paper*, no. 457, for mtg., Mar. 7-8, 1928, 36 pp., 9 figs.

Two groups of alloys were investigated: (1) those rich in aluminum, with nickel, magnesium, iron, zinc, manganese, or silver as second or third constituents; (2) those rich in copper, with tin, zinc, lead, manganese, or aluminum, aluminum alloys were found to possess thermal conductivity of 70-80 per cent that of pure aluminum, while bronzes range from one-fifth to one-tenth of value for copper.

BRONZE, GEAR

Developments in Gear Bronze, T. H. W. Jeacock. *Brass World*, vol. 24, no. 2, Feb. 1928, p. 40, 1 fig.

How addition of nickel improves permanent-mold castings; inclusion of nickel in bronze alloy for gear blanks increases yield point considerably with but slight loss in elongation.

CASTING, CENTRIFUGAL

Spun-Sorbitic Cast Iron. *Automobile Engr.*, vol. 18, no. 238, Feb. 1928, p. 59, 3 figs.

New process for producing cylinder barrels by centrifugal casting; experimental work to determine conditions necessary for successful casting; improvement in resistance to wear; subjecting cylinder castings to special cooling treatment while in mold during rotation.

CASTINGS

CLEANING. Cleaning Room Progress Aids Production of Quality Castings, F. G. Steinebach. *Foundry*, vol. 56, nos. 5 and 6, Mar. 1 and 15, 1928, pp. 179-180, 190, and 214-216, 11 figs.

Mar. 1: Various types of equipment used in cleaning room; water mill used to polish small castings; grinding introduced; compressed air needed; gates and risers on steel castings removed with oxyhydrogen flame. Mar. 15: Several processes used; cleaning department improvements; different types of brushes. (To be continued.)

CAST IRON

DEVELOPMENTS. Recent Developments in Cast Iron, J. G. Pearce. *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 25-26.

It is now recognized that improved cast irons may not only find fields of application entirely their own, but may win back fields previously lost to competing materials; reviews advances made from metallurgical point of view during past 10 years.

ELECTRIC CONDUCTIVITY. Research on the Electric Conductivity of Cast Iron (Studien ueber die elektrische Leitfaehigkeit des Gusseisen), H. Pinsl. *Giesserei-Zeitung (Berlin)*, vol. 25, no. 3, Feb. 1, 1928, pp. 73-83, 16 figs.

Author claims there exists only scant literature on subject of electric resistance of cast iron; reviews work by other investigators, and gives results of his own measurements on different types of castings in relation to their structural constituents; influence of annealing. Diagrams and photomicrographs.

FATIGUE. Fatigue Tests of Cast Iron, H. F. Moore and S. W. Lyon. *Can. Foundryman (Toronto)*, vol. 19, no. 2, Feb. 1928, pp. 11-12 and 36, 3 figs.

Investigation of fatigue strength of several kinds of cast iron recently been made at University of Illinois; specimens cut from castings of simple shape, and cast under carefully controlled foundry conditions; results of static and Brinell tests; results of fatigue tests; each of four lots of cast iron tested showed well-defined fatigue limit.

NICKEL AND CHROMIUM CONTENT. The Influence of Nickel and Chromium on Cast Iron. *Foundry Trade Jl.*, vol. 38, no. 599, Feb. 9, 1928, p. 100.

Review of recently published works by D. M. Houston, R. S. Poister, E. Piwowarsky, Young, Sipp and Roll, and Turner and Hanson.

PROPERTIES. Mechanical and Physical Properties of High-Grade Gray Cast Iron and Principles Underlying Its Production (Hochwertiger Grauguss, seine mechan.-physikal. Eigenschaften und die Grundlagen zu seiner Erzeugung), E Zimmermann. *Zeit. fuer die gesamte Giesseripraxis (Berlin)*, vol. 49, nos. 7, 8, 9 and 10, Feb. 12, 19, 26 and Mar. 4, 1928, pp. 64-65, 71-72, 78-80 and 91-93.

Feb. 12: Structural constituents of alloys from 0 to 1.76 per cent. Feb. 19: Distribution of constituents in white and gray cast iron after solidification. Feb. 26: Iron-carbide system and iron-graphite system. Mar. 4: Lanz pearlitic cast iron. (Continuation of serial.)

TESTING. Colorimetric Methods in the Foundry Laboratory (Kolorimetrische Methoden im Giessereilaboratorium), H. Freund. *Giesserei (Duesseldorf)*, vol. 15, no. 6, Feb. 10, 1928, pp. 133-135, 1 fig.

Describes several modern methods for colorimetric testing of cast iron to determine iron, manganese, copper and titanium content.

CAST IRON, GRAY

Holds Concerted Effort Necessary in the Gray Iron Industry, B. H. Johnson. *Foundry*, vol. 56, no. 5, Mar. 1, 1928, pp. 192-193.

Gray iron castings have been and are being replaced by other materials, and little is being done to improve quality of gray iron or to find new uses for metal; methods of molding improved; concerted effort must be made; standardization of methods of cost keeping necessary; more attention paid to training of apprentices, or molders and operators.

CHROMIUM-NICKEL STEEL

Alloys of High Nickel and Chromium Content, (Les alliages à hautes teneurs en nickel et en chrome), P. Chévenard. *Revue de Métallurgie (Paris)*, vol. 25, no. 1, Jan. 1928, pp. 14-34, 28 figs.

Influence of chromium on properties of nickel; study of ferrous chromium-nickel alloys; influence of chromium on properties of ferronickels; applications. (Concluded.)

BRITTLENESS. Investigation of Brittleness of Annealed Chrome-Nickel Steel (Undersokning av anlopningsskorheten hos kromnickelstal), R. Wijkander. *Jernkontorets Annaler (Stockholm)*, no. 1, 1928, pp. 1-19, 16 figs.

Describes various forms of producing, ingots, their classification, standardization, tempering, annealing; tables of tests of annealed and non-annealed ingots; examination of structure; solution tests in diluted sulphuric acid.

BRITTLENESS. Investigation of the Brittleness of Some Annealed Chrome-Nickel Steels and One Nickel Steel (Undersokning av anlopningsskorhten hos nagra kromnickeloch ett nickelstal), B. Palmgren. *Jernkontorets Annaler (Stockholm)*, no. 1, 1928, pp. 20-25.

Discusses particular conditions and nature of alloys favoring brittleness; difference in appearances of fractures of brittle and tough steels.

CHROMIUM PLATING

PROTECTIVE VALUE. Protective Value of Chromium-Plate, E. M. Baker, and W. L. Pinner. *Soc. Automotive Engrs.—Jl.*, vol. 22, no. 3, Mar. 1928, pp. 331-334, 2 figs.

Rust resistance afforded by electrodeposited coatings of chromium alone and in combination with nickel and copper; chromium alone has little protective value for outdoor exposure; protective value of composite coating; amount of chromium deposited on nickel and copper that increases protective value; proper procedures to obtain maximum protective value at minimum cost.

COPPER ALLOYS

Alpha Phase Boundary of the Copper-nickel-tin System, W. B. Price, C. G. Grant, and A. J. Phillips. *Am. Inst. Min. and Met. Engrs.—Tech. Pub.*, no. 103, Mar. 1928, 12 pp., 25 figs.

800 deg. cent. isotherm of alpha boundary of copper-nickel-tin system was determined; Hansen's determination of alpha phase boundary at low temperatures for copper-tin system has been confirmed; wide range of hardenable copper-nickel-tin alloys has been discovered.

HEAT TREATMENT. On the Quenching and

Tempering of Brass, Bronze, and "Aluminum-Bronze," T. Matsuda. *Inst. of Metals—advance paper*, no. 463, for mtg., Mar. 7-8, 1928, 42 pp., 20 figs.

Effect of quenching and tempering on microstructure, electrical resistance, hardness, and other mechanical properties of brass, bronze and "aluminum-bronze" was examined; it was confirmed that these copper alloys containing proper amount of second metals may be hardened by suitable heat treatment.

COPPER CASTING

Presents Notes on Making Bulky Copper Castings. W. J. Clark. *Foundry*, vol. 56, no. 5, Mar. 1, 1928, pp. 181-184, 6 figs.

Method of pouring heavy copper castings; reasons why copper is difficult metal to cast; impurities resulting from atmospheric contact; charcoal in runner box forms protective covering throughout pouring; manner of gating casting for its running; correct pouring rate; difficulty of adequately feeding against shrinkage; tenure of fluidity over that of casting depends on form, volume and temperature.

COPPER-NICKEL CASTINGS

SPECIFICATIONS. Standards for Castings and Wire. *Brass World*, vol. 24, no. 2, Feb. 1928, pp. 41-42, 2 figs.

Proposed U. S. Government master specifications for copper-nickel alloy castings; method of inspection and tests; standard tension-test specimen.

COPPER-ZINC ALLOYS

The Structure of Copper-Zinc Alloys (Der Aufbau der Kupfer-Zinklegierungen), O. Bauer and M. Hansen. *Mitteilungen aus dem Materialpruefungsamt (Berlin)*, no. 4, 1927, 150 pp., 172 figs.

Solidification and alternation diagram; equilibrium alloys and fields of state of different species of crystals based on thermal and microscopic investigations; assumed affinity of copper with zinc; X-ray structure of copper-zinc alloys; results of test; includes numerous diagrams and photomicrographs, and 5-page bibliography.

CYLINDERS, HOLLOW STEEL

QUENCHING STRESSES. Heat Stresses in Connection with Cooling or Refining of Large Hollow Cylinders (Waermespannungen beim Abkuehlen bzw. Vergueten grosser, hohlgebohrter Zylinder), E. Maurer. *Stahl u. Eisen*, vol. 48, no. 8, Feb. 23, 1928, pp. 225-228, 4 figs.

Determination of temperature curves in quenching of hollow cylinders; exponential equation of heat conduction, and its solution; integral equation of tangential stress developed by Lorenz, and its solution; cylinder of chromium-nickel steel was used for investigation, and it was shown why hollow drilling greatly reduces stresses due to quenching.

ELECTRIC FURNACES

ANNEALING. Notes on a Project for an Electric Cementation Furnace (Notes sur un projet de four électrique de cémentation), L. Delsaux. *Fonderie Moderne (Paris)*, vol. 22, Jan. 10, 1928, pp. 3-6, 4 figs.

Advantages, thermal study and application to cycle of cementation covering conditions of operating, heat losses and power consumed; study of electric furnace for annealing of malleable iron.

ANNEALING. Annealing of Nonferrous Metals in the Electric Furnace, R. M. Keeney. *Am. Electrochem. Soc.—Advance Paper*, no. 8, for mtg. Apr. 26-28, 1928, pp. 59-68.

For this class of work electric furnace has proved more economical than oil or gas, in many cases resulting in annual return of 50 per cent on investment; in rolling mill, however, little progress has been made, although cost of electric annealing on heat basis only compares favorably with cost of oil annealing.

HEAT TREATING. Oven Can Heat 400,000 Pounds of Steel at One Time. *Iron Trade Rev.*, vol. 82, no. 8, Feb. 23, 1928, p. 509, 1 fig.

Description of electric heat treating furnaces of A. O. Smith Corp.; 400,000 lb. of metal heated at one time to maximum of 1650 deg. fahr.; capacity of 3000 kw.; used for heat treatment of steel after fabrication.

HEAT TREATING. Conditions Required for Tempering Furnaces (Les conditions a remplir par les fours à revenir). *Pratique des Industries Mecaniques*, vol. 10, no. 11, Feb. 1928, pp. 467-468, 2 figs.

Description of principal conditions to fulfill for steel tempering with special attention to "Homo" system of electric furnace developed in America.

HEAT TREATING. Automatic Furnace Permits Accurate Heat Control, W. J. Diederichs. *Elec. World*, no. 91, no. 11, Mar. 17, 1928, pp. 561-562, 1 fig.

Application of electric rotary-hearth furnace to hardening of drop-forged wrenches has resulted in improvements in quality of products; wrenches vary in size, and are treated in quantities of 1200 lb. per hour regardless of size.

HIGH FREQUENCY. The New Ajax-Northrop Electric Furnace at the Edgar Allen Works, Sheffield. *Brit. Machine Tool Eng.*, vol. 5, no. 49, Jan.-Feb. 1928, pp. 15-16, 2 figs.

Steel itself is contained in crucible or pot somewhat similar to those used in past; this is surrounded by about inch of heat-insulating sand; around this electric coil is wound carrying high-frequency alternating current; 450 lb. of metal take 45 minutes approximately to melt.

INDUCTION. Electric Smelting Advancement, G. H. Clamer. *Metal Industry (N. Y.)*, vol. 26, no. 3, Mar. 1928, pp. 116-117, 2 figs.

Coreless induction-type furnace (Ajax Northrup); this type of furnace may be operated with high power input and requires no continuous application of power as does submerged register-type furnace; it may in these respects be compared to arc furnace. (Concluded.)

MELTING. Melting of Copper and Brass in Electric Furnaces (La fusion du cuivre et du laiton au four électrique), R. Sevin. *Jl. du Four Electrique (Paris)*, vol. 37, no. 2, Feb. 1928, pp. 38-40, 2 figs.

Describes Ajax Wyatt electric furnace used by Société d'Electro-Métallurgie de Dives and advantages it has in brass and copper melting; also describes Rennerfelt type of electric furnace and gives details of current used.

OPERATION. Operation and Regulation of Electric Furnaces Studied Diagrammatically

(Le fonctionnement et le réglage des fours électriques étudiés par le diagramme), P. Bergeon. *Revue de Métallurgie*, vol. 24, no. 11, Nov. 1927, pp. 683-694, 6 figs.

Diagrams and formulas are given illustrating dependence of power factor on electrical conditions and method of operating electric furnace operated from transformer; results obtained suggest new method of regulating arc furnaces by suitable manipulation of electrodes which is especially advantageous when voltage of primary is adjustable and furnace has relatively high inductance.

ELECTRIC HEATING

Heating by Electricity and the Cost, C. L. Ipsen. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, pp. 175-178, 5 figs.

Analysis of cost of heating which takes into consideration not only initial expenditure for electricity but all contributory items also; desirability of electric heat for most industrial application is unchallenged from every standpoint except that of cost; relative cost of electricity and fuel; relative cost of heating process with fuel and electricity; relative overall cost and quality of product when heated by fuel and electricity.

FERROALLOYS

ELECTROLYTIC PRODUCTION. Electrolytic Manufacture of FerroAlloys (La fabrication électro-métallurgique des ferro alliages), R. Galmard. *Pratique des Industries Mecaniques*, vol. 10, no. 11, Feb. 1928, pp. 463-466.

Treats of manufacture of ferroalloys used for mixing in steel to produce better mechanical qualities; these are ferronickel, ferrochromium, ferrotungsten, ferromolybdenum, ferrotitanum and ferrouranium. (Conclusion of serial.)

FERROMAGNETIC MATERIALS

SPECIFIC HEAT. The Specific Heat of Ferromagnetic Substances, L. F. Bates. *Royal Soc.—Proc. (Lond.)*, vol. 117, no. A 778, Feb. 1, 1928, pp. 680-691, 5 figs.

Thermal and magnetic behavior of simple ferromagnetic compound of manganese and arsenic studied; critical point at 45 deg. cent.; heat is very rapidly absorbed when substance changes from ferromagnetic to paramagnetic state; thermal and magnetic phenomena are imtimately connected; with magnetic change there is associated heat of transformation.

FERRONICKEL

CHROMIUM ADDITION. Alloys of High Nickel and Chromium Content, (Les alliages à hautes teneurs en nickel et en chrome), P. Chévenard. *Revue de Métallurgie (Paris)*, vol. 25, no. 1, Jan. 1928, pp. 14-34, 28 figs.

Influence of chromium on properties of nickel; study of ferrous chromium-nickel alloys; influence of chromium on properties of ferronickels; applications. (Concluded.)

FORGING

The Behaviour of Metals and Alloys During Hot-Forging, W. L. Kent. *Engineering (Lond.)*, vol. 125, no. 3244, Mar. 16, 1928, pp. 331-333, 6 figs.

Research to investigate forging properties of metals and alloys, with view to application of forging tests as measurement of their malleability at high temperatures. Paper read before Inst. of Metals.

The Behaviour of Metals and Alloys During Hot-Forging, W. L. Kent. *Inst. of Metals—advance paper*, no. 462, for mtg., Mar. 7-8, 1928, 18 pp., 6 figs.

Cylindrical specimens of pure metals and some brasses were forged with standard blow of 50 ft. lb. at temperatures up to melting points, and mechanism of hot forging was investigated by measurements of degree of compressions produced and by comparison of Brinell hardness values so obtained; although forging test does not measure malleability of metal or alloy, it will indicate relative forgeability at different temperatures, and also liability for cracking to occur during operation.

FURNACES, FORGING

Modernizing Forging, F. W. Manker. *Gas Age-Rec.*, vol. 61, no. 10, Mar. 10, 1928, pp. 313-314, 4 figs.

Four billet-heating furnaces installed in forge plant of Willys-Overland Co. for bringing crankshaft stock up to heat for forging operation; these furnaces are each 18 ft. long, 4 ft. wide and 1½ ft. high, internal dimensions; they are equipped with pneumatic pushers, inclined hearths, water-cooled skids, and side-door discharge and are fired with gas through water-cooled bruners.

OPERATION. Forge Heating Furnace Operation and Methods on Oil Fired Equipment, J. R. Miller. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, p. 199.

Furnaces in question were regenerative type, oil fired with horse shoe flame.

FURNACES, HEAT TREATING

Automatic Furnaces for Annealing and Heat-Treating. *Am. Mach.*, vol. 68, no. 12, Mar. 22, 1928, p. 492, 4 figs.

Four halftones furnished by Warner Gear Co.; conveyor so timed as to maintain proper heat; hump furnaces used in heat-treating gears; each halftone accompanied by brief description.

TUNNEL. Uses of Continuous Tunnel Furnaces in Metallurgy (Application des fours continus à tunnel en métallurgie), R. Sylvany. *Revue de l'Industrie Minérale (Paris)*, no. 173, Mar. 1, 1928, pp. 73-75, (Supp.), 2 figs.

Types of tunnel furnaces employed in heat treatment of thin plates and malleable castings, with special reference to American practice; advantages of this type of furnace; success of malleable castings in America are attributed largely to its use; fuel-consumption data.

FURNACES, INDUSTRIAL

DESIGN. Practical Industrial Furnace Design, M. H. Mawhinney. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, pp. 189-193 and 197, 8 figs.

Radiation and optical pyrometers; automatic control of temperature and furnace atmosphere with various fuels; advantages of automatic control; gaseous and liquid fuels; automatic pressure control; covers chief principles of operation upon which automatic control is based and clarifies most confusing factors which complicate consideration of furnace control. (Concluded.)

HARDNESS TESTS

Comparison of the Various Methods of Testing the Hardness of Metals, D. L. Mathias.

Instruments, vol. 1, no. 2, Feb. 1928, pp. 87-91.

Different methods described with their application in estimating physical properties of material; comparison of results, obtained over considerable period of time, would be excellent means of gaging success of production; Brinell test; scleroscope use limited; scratch test for testing hardness of metallic coatings; Rockwell machine.

HARDNESS TESTING MACHINES

An Improved Hardness Tester. *Iron Age*, vol. 121, no. 9, Mar. 1, 1928, pp. 602-603, 4 figs.

Accurate and proportional Brinell numerals claimed for British machine developed by Vickers, Ltd.; diamond pyramid indenter pressed into work under low load and at automatically controlled rate; machine is superior for metals of great hardness, and is applicable to finished work and very thin sheets; specially designed micrometer ocular provided; details of operating machine.

HIGH SPEED STEEL

A New Steel that will Cut Manganese Steel, A. S. Martin. *Machy., (N. Y.)*, vol. 34, no. 7, Mar. 1928, pp. 547-548.

Material developed to produce cutting medium that would give greater production than present high-speed steels; machining manganese steel castings; tests were conducted under ordinary shop conditions; cutting speeds and feeds that gave best results; heat treatment required for new steel; results obtained in tests; performance on drilling and other machining operations.

CUTTING. Machining Manganese Steel on a Commercial Basis, A. S. Martin. *Iron Trade Rev.*, vol. 82, no. 9, Mar. 1, 1928, pp. 564-565.

Tests on cutting capacity of new type of high-speed steel conducted by Firth-Sterling Steel Co.; cutting medium gives greater production than standard high-speed steels; cutting manganese steel; tests carried on under ordinary machine-shop conditions; chip formed was very tight and completely curled ribbon of deep blue or brownish gunmetal color; firm chucking desirable.

QUENCHING. What Happens When High Speed Steel Is Quenched, B. H. De Long and F. R. Palmer. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 420-430 and (discussion) 430-434, 11 figs.

Deals with metallography of high-speed steel when tempered at 1100 deg. Fahr. after cooling during quenching to varying temperatures below 1300 deg.; high-speed tools tempered (drawn) before being allowed to become sufficiently cold in quench are brittle due to mixed structures; straightening of high-speed tools may be readily carried out during quenching at between 1300 and 700 deg.

IMPACT TESTING

BARS. Failure of Bars Due to Impact, O. Miyagi. *Mech. World (Manchester)*, vol. 83, no. 2147, Feb. 24, 1928, p. 128.

Stresses in cantilever when load is applied in form of impact; as velocity of impact is increased, section where failure occurs approaches point where load is applied; discusses cantilever, free end of which suddenly acquires velocity as result of blow; experiments made with bars of paraffin wax. From Tohoku Imperial Univ.—Reports, vol. 6, p. 175.

HARDNESS MEASUREMENT. Impact Hardness Testing, I. Class. *Metallurgist Supp. to Engineer, (Lond.)*, Feb. 24, 1928, pp. 22-23, 1 fig.

Discusses measurement of ball hardness by impact methods; apparatus required for such methods has important advantages as regards size, weight and general adaptability over more cumbersome equipment required for ordinary static Brinell test. Abstract translated from V. D. I. Zeit., Nov. 26, 1927.

NOTCHED BAR. History and Present Status of the Notched-Bar Test (Entwicklung und heutiger Stang der Kerbschlagsfrage), A. Hirzenberger. *Mitteilungen des Stat. Technischen Versuchsamtes (Vienna)*, vol. 16, no. 1-3, 1927, pp. 135-144.

History and method and summary of opinions of authorities on its value; bibliographic list of 27 references.

INGOT IRON

Armco Ingot Iron, R. L. Kenyon. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 435-464 and (discussion) 464-472, 10 figs.

Hardness tests on various shapes of Armco ingot iron; results show that rate of scaling of Armco ingot-iron sample shows steady decrease with increase of time, whereas no such regularity is noticed in case of mild steel; it would seem that tightly adherent scale acts as protective coating and so causes rate of scaling to decrease as scale becomes thicker and more protective. Bibliography. (Conclusion.)

GAS CONTENT. International Co-operation in Determining Gases in Metals. *Foundry Trade Jl.*, vol. 38, no. 599, Feb. 9, 1928, p. 92.

U. S. Bureau of Standards distributed sample of ingot iron for gas analyses to University of Sheffield and to Institut fuer Eisenhuettenkunde, Aachen, Germany; results obtained by co-operating laboratories are given.

INGOT STEEL

PROPERTIES. Factors Influencing the Structure and Mechanical Properties of Steel Ingots, H. Bittner. *Iron and Steel World*, vol. 2, no. 2, Feb. 1928, pp. 83-84.

Investigation carried out to determine, whether in case of cooling of ingots and their reheating before rolling, improvement of mechanical properties of rolled material can be obtained; marked influence of treatment on properties of ingots throughout was proved. Translated from Stahl und Eisen.

WORKING. Welding Facts and Figures, D. Richardson and E. W. Birch. *Welding Jl. (Lond.)*, vol. 25, no. 293, Feb. 1928, pp. 41-43, 6 figs.

Handbook for welding engineers. Describes process of working steel from ingots to rolled sections; rolling mills; defects in surfaces of rolled material. (Continuation of serial.)

IRON

CHEMICAL REACTIONS. Equilibrium Investigations of Reduction, Oxidation and Carbonization Phenomena in Iron (Gleichgewichtsuntersuchungen ueber die Reduktions-, oxydations- und Kohlungsvorgaenge beim Eisen). *Stahl u. Eisen*, vol. 48 no. 9, Mar 1, 1928, pp. 269-276, 5 figs.

Polemic between R. Schenck, E. Maurer and W. Bischof, involving discussion of articles by Schenck, published in 1927 issues of Zeit. fuer anorganische u. allgemeine Chemie.

ELECTRIC PROPERTIES. A Method of Testing Iron by Means of a Magnetic Voltmeter (Ueber ein Verfahren der Eisenpruefung mit dem magnetischen Spannungsmesser), W. Wolman. *Archiv fuer Elektrotechnik (Aachen, Germany)*, vol. 19, no. 3, Jan. 25, 1928, pp. 385-404, 28 figs.

Report from Institute of Electrical Engineering of Aachen Institute of Technology on use of magnetic voltmeter; design and calibration of special voltmeter for electric testing of iron, direct measurement of retentivity and remanence, study of hysteresis and other characteristics of unit crystal of mild steel 13 cm. long, under tensile and compressive stresses, etc.

IRON ALLOYS

CEMENTATION. Study of Metallic Cementation. Cementation of Ferrous Alloys by Uranium (Contribution a l'étude des cémentations métalliques. Cémentation des alliages ferreux par l'uranium, J. Laissus. *Revue de Métallurgie (Paris)*, vol. 25, no. 1, Jan. 1928, pp. 50-54, 5 figs.

Influence of temperature and time; influence of carbon content of ferrous alloy on cementation; study of effect of uranium on ferrous alloys. (Concluded.)

IRON CASTINGS

Iron Castings or Steel? *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 18-19.

Discusses certain types of difficulty associated with production of steel castings and casting difficulties associated with use of steel as compared with cast iron; struggle between steel castings and iron for field that might be covered by either will make for advancement of both steel and cast iron.

HEAT TREATMENT. Gray Iron Castings Heat Treated. *Iron Age*, vol. 121, no. 10, Mar. 8, 1928, pp. 663-664, 3 figs.

Smaller parts, some sand cast and others made in permanent molds, pass through continuous furnaces at Ford plant; heat treatment before machining eliminates hard spots; metal softer and easier to machine; after annealing drilling is done more rapidly and there is less breakage of drills; castings made in permanent molds; furnaces and heat-treatment process.

IRON CASTINGS, CHILLED

Chilled Castings, Their Properties and Applications (Der Schalenhartguss, seine Eigenschaften und seine Verwendungsmoeglichkeiten), H. Bator. *Giesserei (Duesseldorf)*, vol. 15, no. 6, Feb. 10, 1928, pp. 121-127, 22 figs.

Historical review of attempts in beginning of past century to produce chilled castings, especially chilled iron rolls, in Germany; with aid of photomicrographs of structure and practical examples, author describes how high-grade chills are produced, properties they should possess and their useful possibilities.

IRON METALLURGY

Effect of Temperature on the Solubility of Iron Oxide in Iron, C. H. Herty, Jr. and E. M. Gaines, Jr. *Am. Inst. Min. and Met. Engrs.—Tech. Pub.*, no. 88, Mar. 1928, 13 pp., 3 figs.

Investigation to determine amount of iron oxide that will dissolve in iron under various conditions; it was thought best to determine solubility under simple slags as first step.

IRON-CHROMIUM ALLOYS

The Alloys of Chromium and Iron. *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 26-28, 2 figs.

Reviews investigations made by Oberhoffer and Esser at Aachen (Stahl u. Eisen, Dec. 1, 1927), who with aid of X-ray examination, have endeavored to rectify somewhat tentative conclusions of earlier work of Pakulla and Oberhoffer; great advance made by these investigations in knowledge of chromium-iron system is to be attributed largely to their perfection of technique of high-temperature melting under vacuum conditions.

Critical Points in Chromium-iron Alloys, A. B. Kinzel. *Am. Inst. Min. and Met. Engrs.—Tech. Pub.*, no. 100, Mar. 1928. 7 pp., 4 figs.

Chromium-iron loop runs from 0 to 12.2 per cent chromium; its upper boundary runs from 1400 to 900 deg. cent., following oblique hyperbola, and its lower boundary runs from 900 deg. at 0 chromium to 900 deg. at 12.2 per cent chromium.

IRON-SILICON ALLOYS

The Constitution of the Iron-silicon Alloys Particularly in Connection with the Properties of Corrosion-resisting Alloys of this Composition, M. G. Corson. *Am. Inst. Min. and Met. Engrs.—Tech. Pub.*, no. 96, Mar. 1928, 47 pp., 63 figs.

Criticism of diagrams of previous investigations; author's main interests have been concentrated in direction of transformations taking place in solid state and in concentration of solid solutions; electric-resistivity and hardness tests; microscopic study and photomicrographs; X-ray analysis; ductility and malleability of iron-silicon alloys; resistance to corrosion; influence of additional elements.

TESTING. Iron-Silicon Equilibrium Diagram. *Iron Age*, vol. 121, no. 11, Mar. 15, 1928, p. 730, 1 fig.

Discussion of iron-silicon alloys including complete equilibrium diagram; X-ray evidence of occurrence of iron silicon subsequently in well annealed specimens; results of studies on higher silicon alloys, by thermal analysis, X-rays, and microscope.

MAGNESIUM

PROPERTIES. Light Metals and Alloys—Aluminum, Magnesium. *U. S. Bur. Standards—Circular*, no. 346, Dec. 12, 1927, 397 pp., 115 figs.

Physical and mechanical properties of aluminum and magnesium and their light alloys, and variation in properties caused by changing composition of alloy, by presence of impurities, mechanical working, changes in conditions of manufacturing operations, and by heat treatment; selection of data available has been made and data checked by representatives of light-alloy industries; equilibrium diagrams for important alloy systems; protection against corrosion. Bibliography.

MAGNESIUM-ZINC ALLOYS

The Constitution of the Alloys of Mag-

nesium and Zinc, R. Chadwick. *Inst. of Metals—advance paper*, no. 449, for mtg., Mar. 8-9, 1928, 14 pp., 19 figs.

Investigation of equilibrium diagram of magnesium-zinc system; both thermal and micrographic methods have been used, system having been investigated at all compositions and down to 200 deg. cent.

MANGANESE STEEL

MACHINERY. Machining Manganese Steel, H. S. Martin. *Ry. Jl.*, vol. 34, no. 3, Mar. 1928, pp. 25-26.

Tests have been conducted on cutting capacity of entirely new type of high-speed steel known as circle C steel; with tools made of steel under test, manganese steel can be commercially machined, using cutting speeds from 1½ to 15 ft per min.; time of cut between grindings of tool runs from 1 to 9 hours.

MATERIALS

X-RAY ANALYSIS. The X-Ray Examination of Materials, G. L. Clark. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, pp. 138-145, 24 figs.

Apparatus; nature of X-ray; current uses; analysis of structure of materials; methods of study and types of information gained; crystallographic patterns; radiography.

X-RAY ANALYSIS. X-ray Tubes for Testing of Construction Materials (Roentgenroehren fuer Werkstoffpruefungen), du Bois. *Chemiker-Zeitung*, vol. 52, no. 10, Feb. 4, 1928, pp. 102-103, 5 figs.

Brief description of various European types of X-ray tubes and apparatus including Siegbahn-Hadding and others manufactured by Philips, Seifert, Leiss and others.

METAL SPRAYING

DEVELOPMENTS. Recent Developments in Metal Spraying, R. A. Parkes. *Metal Industry (Lond.)*, vol. 32, nos. 10 and 11, Mar. 9 and 16, 1928, pp. 249-251 and 273-274, 6 figs.

Mar. 9: Comparative advantages of powder and wire feed; homogeneous coatings; methods of reducing porosity; mechanical means of securing porosity; zinc coatings. Mar. 16: Corrosion resistance; tin, lead, nickel, and iron coatings; spraying with aluminum; cadmium and chromium spraying. (Concluded.)

METALS

CLEANING. The Growth of Industrial Cleaning, D. J. Benoliel. *Metal Industry (N. Y.)*, vol. 26, no. 3, Mar. 1928, pp. 121-123.

Sketches difference between caustic potash and caustic soda, and shows why former is so superior to latter.

COLD WORKING. Historical Note on Density Changes Caused by the Cold-Working of Metals, H. O'Neill. *Inst. of Metals—advance paper*, no. 450, for mtg., Mar. 8-9, 1928, 3 pp., 1 fig.

Priority for observation that its density decreases when metal is cold worked is generally attributed to certain Continental workers, notably to Spring (1891); it appears that Berzelius (1844) may previously have noticed effect, but it is certain that Charles O'Neill of Manchester published careful research upon subject 30 years before work of Spring was printed.

COLORING. Metal Coloring and Decorating, N. Hepburn. *Brass World*, vol. 24, no. 2, Feb. 1928, pp. 51-52, 1 fig.

Study of patina, its use and abuse; acid coloring solution; applying acid solution.

CORROSION. The Relative Corrodibilities of Ferrous and Non-Ferrous Metals and Alloys, J. N. Friend. *Inst. of Metals—advance paper*, no. 456, for mtg., Mar. 7-8, 1928, 23 pp., 12 figs.

Bars of ferrous and non-ferrous metals were exposed to sea action in Bristol Channel for four years, and account is given of 14 non-ferrous bars; losses in weight, depths of pitting, reduction in diameter, and fall in tensile strength in consequence of corrosion are correlated; metals examined included tin, lead, nickel, zinc, aluminum, and various coppers and brasses.

CORROSION. Corrosion of Metals and Its Prevention (Metallzerfall und Metallschutz), W. H. Creutzfeldt. *Stahl u. Eisen*, vol. 48, no. 8, Feb. 23, 1928, pp. 228-229.

Discusses four main groups of metal disintegration: direct oxidation at high temperatures; corrosion due to atmospheric influences; corrosion by natural waters; and corrosion by strong chemicals, such as acids, brines, etc.; protective measures for each of these classifications. Abstract from Archiv fuer das Eisenhuettenwesen, vol. 1, Dec. 1927, p. 427.

DEFORMATION. Plastic Deformation and Fracture of Metals, W. Rosenhain. *Iron and Steel World*, vol. 2, no. 2, Feb. 1928, pp. 105-110.

Straining of crystal lattice slip, and orientation of crystals in cold-worked metal. From address before Int. Congress for Testing Materials of Amsterdam.

DIFFUSION. Grain Growth in Metals Caused by Diffusion, F. C. Kelley. *Am. Inst. Min. and Met. Engrs.—Tech. Pub.*, no. 89, Mar. 1928, 7 pp., 9 figs.

Diffusion of metals in iron; method of grain growth; force of diffusion; different forms of grain growth; review of recent work in Germany.

DILATOMETRIC EXAMINATION. The Dilatometric Study of Light Metals, M. Hass. *Inst. of Metals—advance paper*, no. 460, for mtg., Mar. 7-8, 1928, 16 pp., 19 figs.

Technical details concerning dilatometric examination of light metals; also improvements to this end in Oberhoffer-Esser dilatometer; differential dilatometric curves of pure aluminum, silumin, aluminum-copper, and duralumin obtained with Chevenard and Oberhoffer-Esser dilatometer are shown and discussed.

ELECTRON THEORY. The Restored Electron Theory of Metals and Thermionic Formulae, R. H. Fowler. *Royal Soc.—Proc. (Lond.)*, vol. 117, no. A 778, Feb. 1, 1928, pp. 549-552.

Calculation of density of evaporated electrons in equilibrium with heated metal: calculation bears on well-known formula for thermionic emission; establishes vapor-pressure formula on new basis without particularized assumptions as to mechanism of emission and absorption of electrons; equilibrium state of assembly of electrons considered in two phases.

FATIGUE. Fatigue in Relation to Phenomena in Single Crystals (Ermuedung vom

Standpunkt der Vorgaenge im Einkristall), E. Schmid. *Zeit. fuer Metallkunde (Berlin)*, vol. 20, no. 2, Feb. 1928, pp. 69-74 and (discussion) 75-77, 22 figs.

Fatigue tests on single crystals show that plastic deformation takes place through activity of same slip elements as are effective in static tensile test; increased embrittlement of fatigued crystals is traced to lack of uniformity in strain hardening, etc.

FATIGUE. Changes in Mechanical Properties of Metal Due to Fatique (Welche Veraenderungen erleiden die mechanischen Eigenschaften durch Ermuedung), J. Czochralski and E. Henkel. *Zeit. fuer Metallkunde (Berlin)*, vol. 20, no. 2, Feb. 1928, pp. 58-62 and (discussion) 62-63, 16 figs. partly on supp. plate.

Results of fatigue testing show changes in property, especially of annealed metals; means of preventing fatigue failures.

FATIGUE. Fatigue of Metals Due to Static Permanent Load (Ermuedung durch kritische statische Dauerbelastung), G. Welter. *Zeit. fuer Metallkunde (Berlin)*, vol. 20, no. 2, Feb. 1928, pp. 51-56 and (discussion) 56-57, 15 figs.

Investigation of influence of time on properties of materials based on critical load limit; results of tests with iron, brass, aluminum and magnesium alloys; influence of temperature on properties of material, and dependence of strength on two factors, time and temperature, is shown diagrammatically.

FATIGUE. Elasticity, Static and Endurance Tests (Elastizitaet, statische Versuche und Dauerpruefung), W. Kuntze, G. Sachs and H. Sieglerschmidt. *Zeit. fuer Metallkunde (Berlin)*, vol. 20, no. 2, Feb. 1928, pp. 64-68, 14 figs.

Discusses problem of fatigue; elasticity of copper under different treatment methods; incomplete elasticity and fatigue; bending tests.

FATIGUE. Fatigue Phenomena, H. J. Gough. *Engineering (Lond.)*, vol. 125, no. 3242, Mar. 2, 1928, p. 264.

Third Cantor lecture, dealing with characteristics of deformation of single crystals of zinc, aluminum, tungsten, brass, and iron, under static forces, and behaviour of single crystals of aluminum under fatigue stresses.

FATIGUE. Fatigue Phenomena. *Engineering (Lond.)*, vol. 125, no. 3241, Feb. 24, 1928, pp. 232-233.

Second Cantor lecture made special reference to single crystals; reviews three epochs in history of fatigue testing; one of more interesting phenomena is fact, regarded as definitely established, that metal subjected to repetitions of safe range of stress finally achieved state in which, although no further permanent set would appear, strain hysteresis was present, and would persist indefinitely without causing fracture of material.

FATIGUE. Fatigue Phenomena. H. J. Gough. *Engineering*, vol. 125, no. 3240, Feb. 17, 1928, pp. 200-201.

Review of first of series of Cantor lectures presented at Roy. Soc. of Arts; fatigue of metals is defined as behavior of metals under repeated cycles of stress; mathematical theory of elasticity indicates clearly that uniform stress distribution would not be obtained at any cross-section where form or size was changing, and that, where change was rapid, stress concentration effects produced would be large.

MECHANICAL PROPERTIES. Normal and Shear Stress in the Testing of Materials, P. Ludwik. *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 28-30, 2 figs.

It appears that too high shear resistance, as evidenced by too high dynamic elastic limit, may be undesirable; on the other hand, high resistance to shear is desirable particularly for high endurance to alternating stress; high impact strength and high endurance can only be obtained together by maintaining shear resistance and increasing cohesion. Abstract translated from V. D. I. Zeit. Oct. 28, 1927.

PERMANENT FRACTURE. Permanent Fracture of Metals (Dauerbruch als dynamische und schwingungstechnische Erscheinung), W. Hort. *Zeit. fuer Metallkunde (Berlin)*, vol. 20, no. 2, Feb. 1928, pp. 40-43 and (discussion) 43-44, 18 figs.

Discusses Woehler tests and their significance; stresses in machine structures; vibration theory; characteristics of permanent-fracture occurrences; notch effects, vibration phenomena and impact effects; endurance; testing of material.

TESTING. The Importance of three-Dimensional Stresses in Materials Testing (Die Bedeutung raeumlicher Spannungszustaende fuer die Werkstoffpruefung), P. Ludwik. *Archiv fuer das Eisenhuettenwesen (Duesseldorf)*, vol. 1, no. 8, Feb. 1928, pp. 537-542, 12 figs.

Three-Dimensional stress conditions under compressive and tensile stress, and with heat, shrinkage and expansion stresses; comparative tension and torsion test; notch effect with static, dynamic and alternating stress; limit of elasticity; limit of fatigue and damping capacity.

UPSETTING TESTS. Technical Upsetting Problems (Technische Stauchprobleme), E. Siebel. *Archiv fuer das Eisenhuettenwesen (Duesseldorf)*, vol. 1, no. 8, Feb. 1928, pp. 543-548, 13 figs.

Stress conditions in technical upsetting process; influence of friction on deformation; conical upsetting process; strain distribution in connection with stretching; stress conditions with rolling and spreading; transverse upsetting of cylindrical bodies; hole formation with diagonal rolling.

VIBRATION STRESSES. Surface Sensitivity and Internal Strength of Materials under Oscillating Stresses (Oberflaechenempfindlichkeit und innere Arbeitsaufnahme der Werkstoffe bei Schwingungsbeanspruchung), E. Lehr. *Zeit. fuer Metallkunde (Berlin)*, vol. 20, no. 2, Feb. 1928, pp. 78-85 and (discussion) 85-90, 10 figs.

Explains basic functions of dynamic testing of materials; fundamental problems of pure vibration stress; internal strength of structure; presents table showing permanent bending strength under surface strain and 3000 load variations per minute.

X-RAY ANALYSIS. Modern Research on the Structure of Metals, W. P. Davey, *Franklin Inst.—Jl.*, vol. 205, no. 2, Feb. 1928, pp. 221-228.

Use of X-rays in effort to solve factory problems; aid in development work; discovery of new facts on which to base future factory processes; study of mechanical working of metals on preferred orientation of crystals in metal.

X-RAY ANALYSIS. High Speed, High Voltage X-Ray Diffraction Analysis of Metals, A. St. John. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 485-492, 5 figs.

Quick and convenient method of X-ray diffraction analysis is modification of usual "pinhole" method using tungsten radiation at 200,000 volts as in radiographing castings, so that powerful beam passes through ⅛ inch of steel; exposures of two hours or less are sufficient; method has been applied to brass, tin and steel in study of mechanical working, heat treatment, extrusion, aging and effect of exposure to gases.

X-RAY ANALYSIS. X-Rays: A New Tool in the Foundry. *Iron Age*, vol. 121, no. 10, Mar. 8. 1928, pp. 655-656, 4 figs.

Examination of X-ray before machining castings reveals hidden defects and reduces foundry costs; two cases cited; with gray iron or steel castings it is now possible to X-ray through thickness of 3½ in.; such flaws as blowholes, cracks, bubbles and foreign material are relatively easy to detect in one or two exposures; X-ray equipment of low cost utilized for aluminum-alloy castings; examining first run of castings.

X-RAY ANALYSIS. Using X-Rays to Inspect Materials for Internal Defects, H. R. Isenburger. *Foundry*, vol. 56, no. 5, Mar. 1, 1928, pp. 171-173, 7 figs.

Metal radioscopy discussed; based on penetrating power of X-rays; used for testing of raw materials or half-finished manufactures such as castings and soldered or welding seams, for faults within materials; high-capacity appratus needed; excessive increase in voltage not advisable; may become routine; various methods available.

METALS, COLD WORKED

STRUCTURE. Changes in Structure and Electric Resistance of Cold-Worked Metals (Die Anderungen der Struktur und des elektrischen Widerstandes bei der Kaltbearbeitung von Metallen), G. Tammann and M. Straumanis. *Zeit. fuer Anorganische u. Allgemeine Chemie (Leipzig)*, vol. 169, no. 4, Feb. 11, 1928, pp. 365-380, 11 figs.

Reports experiments at Institute of Physical Chemistry of University of Goettingen; changes in orientation of crystallites in drawn copper wire; change in electrical resistance of heat-treated copper and silver wires; change in orientation of crystallites of heat-treated wires; relation between structure, electric resistance and elastic properties.

METALS, MOLTEN

HEAT OF MIXTURE. The Heat of Mixture of Molten Metals. *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 23-25, 4 figs.

Review of work by M. Kawakami, who has measured heat of mixing of potassium-sodium, mercury-tin, cadmium-lead, tin-zinc, bismuth-zinc, cadmium-zinc, lead-zinc, mercury-potassium, mercury-sodium, zinc-antimony and cadmium-magnesium systems.

SURFACE TENSION. The Surface Tension of Molten Metals With a Determination of the Capillary Constant of Copper, E. E. Lubman. *Univ. of Ill.—Bul.*, vol. 25, no. 22, Jan. 31, 1928, 49 pp., 26 figs.

Surface Tension is governing factor in all processes of welding, soldering, and joining; in casting operations where sharp outline is necessary, surface tension of molten metal is governing factor; theoretical aspect of problem; apparatus used in investigation.

METALS, SOFT

COLD WORKING. The Ball Hardness and the Cold-Working of Soft Metals and Eutectics, F. Hargreaves. *Inst. of Metals—advance paper*, no. 461, for mtg., Mar. 7-8, 1928, 27 pp., 6 figs.

Equation is given which expresses relation between diameter of impression and duration of loading for number of soft metals and eutectics.

METALLURGY

Developments. Developments in Metallurgy During 1927, J. Silberstein. *Blast Furnace and Steel Plant*, vol. 16, no. 2, Feb. 1928, pp. 255-257.

Among topics considered are: ferrous metallurgy, centrifugal casting, silicon alloys, welding application of X-rays, chromium plating and non-ferrous metallurgy.

PATENTS. Reviews of Recent Patents, N. Littell. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 497-499, 4 figs.

Review of patents covering heat-treating and heading bolts, improving aluminum alloys, making malleable-iron castings, pickling apparatus, heat treatment of metals, etc.

PATENTS. Patents. *Metal Industry, (N. Y.)*, vol. 26, no. 3, Mar. 1928, p. 133, 2 figs.

Patents covering process of producing corrosion-resisting coating on iron and steel, tapping plug for metallurgical furnaces; rust-proofing; solder; lead product; corrosion-resisting alloy; bearing metals; process and apparatus for extracting zinc; nitrocellulose lacquer; apparatus for heat-treating metals; tinning articles, etc.

PATENTS. New Patents. *Metal Industry (Lond.)*, vol. 32, no. 7, Feb. 17, 1928, pp. 191-192.

Review of recent patents for metal pipes, alloys and porous metals.

PATENTS. New Patents. *Metal Industry (Lond.)*, vol. 32, no. 6, Feb. 10, 1928, p. 166.

Abstracts of new patents on treating zirconium ores; raising yield point of steel alloys by mechanical treatment; malleable alloys of nickel, copper, and iron; aluminum alloys and hardening, etc., screw-cutting taps.

PATENTS. New Patents. *Metal Industry (Lond.)*, vol. 32, no. 8, Feb. 24, 1928, p. 215.

Abstract of new patents on electrolysis, iron alloys and metal catalysts.

METALLURGICAL MATERIALS

Metallurgical Materials. *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 17-18.

Discusses substances which are materials of metallurgist, whether he works at reduction of metals from ores, at their subsequent refining, or their working up into cast or wrought materials, such as fuel, coal or coke, and refractory bodies of which furnaces of all kinds are constructed; also molding sands and number of accessory materials; points out necessity of applying modern methods of testing to these materials.

METALLURGICAL RESEARCH

In the Realm of Metallurgy—New Equipment and Materials. *Automotive Industries*, vol. 38, no. 12, Mar. 24, 1928, pp. 486-488.

Case-hardening process to improve resistance of mechanical parts to torsional and bending stresses studied by J. Miller and applied by Pierce-Arrow Motor Car Co.; surface tension of molten metals studied by E. E. Libman at University of Illinois; Bureau of Standards study of air-hardening steels for use as rivets for armor assembly, and investigation of expansion of alloys.

NICKEL

UTILIZATION. Status of French Industry in the Use of Nickel (Ou en est l'industrie francaise dans les emplois du nickel), J. Dhavernas. *Revue de Métallurgie*, vol. 25, no. 1, Jan. 1928, pp. 44-49.

Examines pure nickel when used in plating; non-ferrous and ferrous alloys of nickel; use of nickel in iron and steel castings.

NICKEL ALLOYS

PROPERTIES. Some Interesting Properties of Alloys of Nickel, W. T. Griffiths. *Chem. Age (Lond.)*, vol. 18, no. 449, Feb. 4, 1928, pp. 98-99.

Coefficient of expansion of nickel-iron alloy containing 36 per cent nickel is very small near ordinary temperatures; nickel itself possesses considerable degree of resistance to corrosion, and this property it passes on to its various alloys; oxidation and high-temperature-resisting steels; nickel-chromium-iron and nickel-chromium alloys.

NICKEL METALLURGY

Nickel, its Metallurgy and its Applications (Le nickel, sa metallurgie et ses applications). *Revue Générale de l'Electrité (Paris)*, vol. 23, no. 10, Mar. 10, 1928, pp. 455-461.

History of nickel; principles of nickel metallurgy; nickel from New Caledonia, and from Canada; applications of nickel, casting, alloys, plating. Review of papers presented at Conservatoire National des Arts et Métiers during "Nickel Week" in Paris.

NICKEL STEEL

Irregular Nickel Steels and their Uses (Les anomalies des aciers au nickel et leurs applications), C. E. Guillaume. *Revue de Métallurgie (Paris)*, vol. 25, no. 1, Jan. 1928, pp. 35-43, 11 figs.

Sketch of properties of nickel when alloyed with iron and irregularities found; effect of additions on elongation of nickel steel; study of elasticity and stability; properties of invar. Address given at Conservatoire des Arts et Metiers.

MANUFACTURE. Alloy Steels, Their Manufacture, Properties and Uses, H. C. H. Carpenter. *Royal Soc. Arts—Jl.*, vol. 76, no. 3925, Feb. 10, 1928, pp. 302-322, 2 figs.

Third Cantor lecture, dealing with nickel steels, nickel-chromium steels, nickel-chromium-molybdenum steels; manufacture and working; uses; combined effect of nickel and chromium on change points of carbon steels; composition and properties.

NON-FERROUS METALS

MELTING. Melting Non-Ferrous Metals, N. R. Stansel. *Gen. Elec. Rev.*, vol. 31, no. 3, Mar. 1928, pp. 125-135, 16 figs.

Pouring temperatures; factors in melting; electric melting furnaces; two types of induction furnaces in use today, viz., core and coreless type; melting non-ferrous metals. (Continuation of serial.)

RESEARCH. Institute of Metals—Proceedings at Twentieth Annual Meeting. *Metal Industry (Lond.)*, vol. 32, no. 10, Mar. 9, 1928, pp. 255-258, 3 figs.

Account of meeting and abstracts of papers read, as follows: Ball Hardness and Cold Working of Soft Metals and Eutectics, F. Hargreaves; Deterioration of Lead Cable Sheathing, S. Beckinsale and H. Waterhouse; Shrinkage Cavities in Alloys, W. A. Cowan; Corrodibilities of Ferrous and Non-Ferrous Metals and Alloys, J. N. Friend; Influence of Dissolved Gases on Soundness of 70:30 Brass Ingots, G. L. Bailey; Behavior of Metals and Alloys During Hot Forging, W. L. Kent; etc.

RESEARCH. Institute of Metals Meeting. *Metal Industry (Lond.)*, vol. 32, no. 11, Mar. 16, 1928, pp. 279-280.

Abstracts of papers as follows: Effect of Quenching and Tempering on Mechanical Properties of Standard Silver, A. L. Norbury; Constitution of Alloys of Magnesium and Zinc, R. Chadwick; Quenching and Tempering of Brass, Bronze, and Aluminum-Bronze, T. Matsuda; Thermal and Electrical Conductivity of Aluminum Alloys and Bronzes, E. Griffiths and F. H. Schofield; Alloys of Zirconium, T. E. Allibone and C. Sykes.

OIL BURNERS

Domestic and Commercial Oil Burners, G. Spencer. *Plumbers Trade Jl.*, vol. 84, no. 4, Feb. 15, 1928, pp. 408 and 456, 2 figs.

Deals with Atlas burner; some of its specifications: natural draft, gravity feed, hot plate, manual ignition and temperature control. (Continuation of serial.)

OIL HEATING RESEARCH

The Modern Oil Heating Reasearch Laboratory, O. C. Schroeder. *Fuel Oil*, vol. 6, no. 9, Mar. 1928, pp. 21-22, 1 fig.

Methods and equipment of laboratory of Automatic Burner Corp., equipped, in general way, to handle all of various electrical, chemical and combustion tests and research necessary for continuous improvement in domestic oil burners.

ORDNANCE MANUFACTURE

Making Big Guns at the Watertown Arsenal, J. B. Nealey. *Machy. (N. Y.)*, vol. 34, no. 7, Mar. 1928, pp. 542-545, 10 figs.

Some of unusual equipment and few outstanding operations; guns ranging in size from 1½ in. to 9½ in. are manufactured, starting with making of steel, for which three large open-hearth furnaces with all necessary auxiliary equipment are provided; heat treatment of gun forgings; laboratories are engaged in research and testing; new method of making guns without outer jackets.

PHOTOMICROGRAPHY

MECHANICAL ENGINEERS APPLICATIONS. Photomicrography and Its Application to Mechanical Engineering, F. F. Lucas. *Mech. Eng.*, vol. 50, no. 3, Mar. 1928, pp. 205-212, 13 figs.

Description of equipment of Bell Telephone Laboratories for technical microscopy, together with particulars regarding application of high-power metallography to study of structures found in hardened steel.

PICKLING (METALS)

Practical Features of Pickling, S. G Imhoff. *Iron Trade Rev.*, vol. 82, no. 9, Mar. 1, 1928, pp. 557-559 and 565, 2 figs.

Pickling fumes, ventilation and by-products discussed; chemical action of acids on metals classified; eliminating destructive fumes; tank capacity important; natural ventilation removing fumes through roof unsatisfactory; ventilating efficiency depends upon efficiency of fan and duct system, and proper practical application of ventilating principles; pickling by-products resolves itself into question of amount of acid wasted, and recovery of this acid. (Continuation of serial.)

Practical Features of Pickling, W. C. Imhoff. *Iron Trade Rev.*, vol. 82, no. 11, Mar. 15, 1928, pp. 677-679 and 684, 1 fig.

Chemistry of pickling; chemical reactions that take place in pickling begin with smallest known particle, electron; phases and conditions of hydrogen; sulphuric, muriatic, nitric, and hydrofluoric acids used in pickling; sulphuric most important; different reactions taking place between metals and sulphuric acid of different strengths; chemistry of black deposit, or black smudge, of pickling solutions.

RAILROADS

TIES, STEEL. Steel Ties for American Railroads, H. J. Jones. *Iron Age*, vol. 121, no. 10, Mar. 8, 1928, p. 670, 1 fig.

Form of steel tie which has distinct advantages described; answers to many objections; cost of manufacturing should be reasonable as section of plate as rolled is of easy rolling design; two forms of rail fastenings; rail seats must have correct and necessary tilt or angle; fastenings should be designed so as to allow necessary adjustments for gage widening or curves.

REFRACTORY MATERIALS

Refractories Are Given Extensive Discussion in Divisional Meeting. *Ceramic Age*, vol. 2, no. 2, Feb. 1928, pp. 57-60.

Raw materials, laboratory operations, furnace linings, glass-house refractories and other topics are discussed; laboratory slag tests for refractories; effect of reducing agents on firebrick; future uses of clays.

PROPERTIES. The Important Properties and Requirements of Some Special Refactories, M. F. Beecher. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 473-483 and (discussion) 483-484 and 492, 2 figs.

Author points out how fused alumina, silicon carbide and combinations of silica and alumina as now manufactured offer properties which are superior to those of clay refractories; these manufactured refractories are all electric-furnace products and are obtained under variety of trade names; common causes of failure in refractories.

REFRACTORIES

HEAT PENETRATION. Heat Penetration in Refractories, M. C. Booze. *Am. Refractories Inst.—Tech. Bul.*, no. 19, Jan. 1928, 3 pp.

Radiation in modern high-temperature industrial furnaces more important factor in transferring heat to furnace walls; resistance of coating will depend upon surface characteristics; cooling by means of air or water boxes reduces outer face temperature without affecting temperature of hot face; time factor in determining heat penetration.

SPRINGS, LEAF

MANUFACTURE. Machine to Curve and Harden Spring Leaves (Machine à cintrer et tremper les lames de ressort). *Industrie des Voies Ferrees et des Transport Automobiles*, vol. 22, no. 253, Jan. 1928, pp. 15-19, 10 figs.

Machine developed by Tramway Co. of Amiens is described, and its operation.

STAINLESS STEEL

The Metal Apso (Note sur le métal Apso), Chaudoye. *Chaleur et Industrie (Paris)*, vol. 9, no. 94, Feb. 1928, p. 102.

New steel, non-corrosive, easily galvanized, good painting qualities; its applications.

MODEL MAKING. About Stainless Steels for Model-Making. *Model Engr.*, vol. 58, no. 1397, Feb. 16, 1928, pp. 143-146, 2 figs.

Heat treatment, soldering and brazing Firth's stainless and Staybrite steel for use in model making; casting and forging stainless and staybrite; bending and flanging; jointing; soft and silver soldering; welding; boiler making. (To be concluded.)

MODEL MAKING. About Stainless Steel for Model-Making. *Model Engr. (Lond.)*, vol. 58, no. 1398, Feb. 23, 1928, pp. 170-172, 1 fig.

Machining operations and working with hand tools; plain turning; screw cutting; screw-cutting tolerance; planing and shaping; drilling; tapping; screwing; sawing. (Continuation of serial.)

PROPERTIES. Systematic View of Stainless Steels, F. R. Palmer. *Iron Age*, vol. 121, no. 11, Mar. 15, 1928, pp. 729-730.

High-chromium steels classified into three groups; properties briefly described and utility for various purposes noted; analysis; heat treatment; toughness; grain growth; hot-working and cold-working qualities; machinability; riveting; welding; corrosion resistance; scale resistance; strength at elevated temperatures. See also Iron Trade Rev., vol. 82, no. 11, Mar. 15, 1928, pp. 680-681, 1 fig.

PROPERTIES. The A-B-C of Corrosion Resisting Steels, F. R. Palmer. *Chem. and Met. Eng.*, vol. 35, no. 3, Mar. 1928, p. 149.

Groups brands of stainless steel made in United States into three groups; general properties of each group have been tabulated without attempt to extend table beyond mere delineation of group characteristics.

STEEL CASTINGS

Iron Castings or Steel? *Metallurgist (Supp. to Engineer, Lond.)*, Feb. 24, 1928, pp. 18-19.

Discusses certain types of difficulty associated with production of steel castings and casting difficulties associated with use of steel as compared with cast iron; struggle between steel castings and iron for field that

might be covered by either will make for advancement of both steel and cast iron.

MANUFACTURE. Steel Foundry Triples Staff in Past Two Years, W. H. Martin. *Can. Machy., (Toronto)*, vol. 39, no. 5, Mar. 8, 1928, pp. 32-33 and 63, 5 figs.

Describes foundry of Joliette Steel Ltd.; production of steel castings, largely manganese and to lesser extent carbon-steel products; all steel is made by electric-furnace process, scrap steel being used throughout; reversible dipper teeth with replaceable wearing edges; five core ovens maintained in constant use for drying molds and cores; sand ramming accomplished by pneumatic rammers.

SHRINKAGE. The Shrinkage of Steel Castings (Beitrag zur Schwindung von Stahlguss), F. Koerber and G. Schitzkowski. *Stahl u. Eisen (Duesseldorf)*, vol. 48, no. 6, Feb. 9, 1928, pp. 172-178, 15 figs.

Investigations of crack formation; influence of chemical composition on shrinkage; movements of large gear and disk-wheel castings during shrinkage. (Conclusion.)

TESTING. The Tensile Testing of Steel Castings. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, pp. 163-166, 2 figs.

Methods of determining physical properties by testing machine are discussed; proper and improper location of test coupons; tensile strength and yield point; advisable precautions in tensile testing; coupons for tensile test specimens. Abstracted from Research Group News.

STEEL

AMMONIA SYNTHESIS, EFFECT OF. Deterioration of Steels in the Synthesis of Ammonia, J. S. Vanick, W. W. de Sveshnikoff, and J. G. Thompson. *U. S. Bur. Standards—Technologic Papers*, no. 361, Nov. 5, 1927, pp. 199-233, 17 figs.

10 commercial steels, subjected to working conditions of 500 deg. cent., 100-atmosphere pressure, and 8.3 per cent ammonia yielded results which indicated that: carbon content should be low; increasing chromium was helpful; tungsten was useful; second test made upon series of chrome-vanadium steels showed that: low carbon content was desirable; vanadium contributed no perceptible improvement; chromium in amount of 2.25 per cent stopped selective penetration and intergranular fissuring and limited depth of penetration.

CEMENTATION. Composition and Value of Mixtures Used for Steel Cementation (La composition et la valeur des mélanges employés pour la cémentation de l'acier). *Génie Civil (Paris)*, vol. 92, no. 9, Mar. 3, 1928, p. 218.

Powders used are divided into 5 groups which are treated in detail.

COLD WORKING. Influence of Varying Degrees of Cold Working on the Hardness of Mild Steel, G. A. Edwards and K. Kuwads. *Iron and Steel World*, vol. 2, no. 2, Feb. 1928, pp. 99-104, 13 figs.

Experiments to determine influence of varying degrees of cold work, in form of cold-rolling, in direction of increasing hardness of mild steel, and temperatures at which this additional hardness is removed; curves and photomicrography. From paper presented before Brit. Iron & Steel Inst.

CORROSION. Passivity and Corrosion, U. R. Evans. *Metal Industry (Lond.)*, vol. 32, no. 9, Mar. 1928, pp. 231-232, 2 figs.

Thin films responsible for passivity; thicker films responsible for temper colors; passivity in steels; distribution of corrosion; bright colors in central zone. Based upon lecture delivered at Manchester Univ., Jan. 31, 1928.

DEVELOPMENTS. Defines Engineering Trends in Steel, B. D. Saklatwalla. *Iron Age*, vol. 121, no. 9, Mar. 1, 1928, pp. 613-614.

Recent developments reviewed by American metallurgist; expansion and effect of alloy steels; biological concept of metallurgy of steel suggested; growth of alloy-steel industry; present status of testing; proper trend in steel research; discussion. Abstract of paper presented at Am. Section of Soc. Chem. Industry.

HARDENING. The Theory of Steel Hardening (Die Theorie der Stahlhaertung), K. Honda. *Archiv fuer das Eisenhuettenwesen (Duesseldorf)*, vol. 1, no. 8, Feb. 1928, pp. 527-533 and (discussion) 534-536, 18 figs.

Discusses two types of martensite; change of atom arrangement in conversion of austenite into martensite; hardness cracks and internal stresses; hardness of cooled steels and changes due to annealing.

HARDENING MECHANISM. The Theory of Steel Hardening (Die Theorie der Stahlhartung), K. Honda. *Stahl u. Eisen*, vol. 48, no. 9, Mar. 1, 1928, pp. 263-264.

Results of author's investigations on volume change during transformation of austenite into alpha martensite. Abstract from Archiv fuer das Eisenhuettenwesen, vol. 1, Jan., 1928, p. 527.

HEAT TREATMENT—FAULT LOCATION. Tests in Locating Faults of Treatment, J. D. Gat. *Heat Treating and Forging*, vol. 14, no. 2, Feb, 1928, pp. 146-149.

Describes means for differentiating between faults due to incorrect treatment and those traceable to steel quality; causes of failure and their correction; annealing; spheroidizing and machinability; burnt steel.

HEAT TREATMENT — TEMPERATURE CONTROL. The Control of Temperature in Heat Treating, G. C. Davis. *Heat Treating and Forging*, vol. 14, no. 2, Feb. 1928, pp. 199-200.

Final temperature of work being heated that is interesting; great steps forward have been made in approach to this ideal heating by growing use of liquids for heating; in case of carbon-steel hardening, there are great possibilities ahead for improving heating of work.

MACHINABILITY TESTING. Testing the Machinability of Materials (Die Pruefung der Bearbeitbarkeit), F. Rapatz and K. Krekeler. *Stahl u. Eisen*, vol. 48, no. 9, Mar. 1, 1928, pp. 257-261, 12 figs.

Investigations of practical adaptability of different testing methods; tests were carried out in soft ingot steels, chromium-nickel steels, and tool steels, and include hardness drill test, tool-thrust test, torsion test, etc.; includes diagrams and photomicrographs.

PASSIVITY. Passivity and Corrosion, U. R. Evans. *Metal Industry (Lond.)*, vol. 32, no. 9, Mar. 2, 1928, pp. 231-232, 2 figs.

Thin films responsible for passivity; thicker films responsible for temper colors; passivity

in steels; distribution of corrosion; bright colors in central zone. Based upon lecture delivered at Manchester Univ., Jan. 31, 1928.

PROPERTIES. A Contribution to the Theory of Hardening and the Constitution of Steel, Z. Jeffries. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 369-404, 20 figs.

Conclusions are adopted that carbon-steel austenite is gamma iron containing carbon in atomic dispersion; freshly formed carbon steel martensite is alpha iron containing carbon largely in atomic dispersion; carbon-steel martensite aged at room temperature or somewhat above contains myriads of particles of iron carbide; when acicular martensite forms orientations of new alpha iron grains have some relations to orientation of parent austenite.

PROPERTIES. Steel Practice Determines Quality, H. D. Hubbard. *Iron Age*, vol. 121, no. 10, Mar. 8, 1928, p. 662.

Those elements making inferior steel are not reported in conventional chemical analysis; furnace practice to be considered as vital factor when investigating effects of alloying elements and gases in simple steels; all insolubles are harmful to steel; manganese important at end; silicon is medicine for steel.

QUENCHING STRESSES—HOLLOW CYLINDERS. Heat Stresses in Connection with Cooling or Refining of Large Hollow Cylinders (Waermespannungen beim Abkuehlen bzw. Vergueten grosser, hohlgebohrter Zylinder), E. Maurer. *Stahl u. Eisen*, vol. 48, no. 8, Feb. 23, 1928, pp. 225-228, 4 figs.

Determination of temperature curves in quenching of hollow cylinders; exponential equation of heat conduction, and its solution; integral equation of tangential stress developed by Lorenz, and its solution; cylinder of chromium-nickel steel was used for investigation, and it was shown why hollow drilling greatly reduces stresses due to quenching.

STRENGTH AT HIGH TEMPERATURES. Determining Endurance of Steel at High Temperatures (Ermittlung der Dauerstandfestigkeit von Stahl bei erhoehten Temperaturen), F. Koerber. *Zeit. fuer Metallkunde (Berlin)*, vol. 20, no. 2, Feb. 1928, pp. 45-49 and (discussion) 49-50, 13 figs.

Points to necessity of testing materials at high temperatures; inadequacy of usual hot tensile tests; influence of time; endurance strength as limit load for continuous deformation; results of new tests; study of expansion; importance of strain hardening and recrystallization; simplified method for determination of endurance.

STEEL, AIRCRAFT

Steel for Aircraft Construction, E. A. Richardson. *Am. Inst. Min. and Met. Engrs.—Tech. Pub.*, no. 94, Mar. 1928, 19 pp.

Principles of airplane construction; structural design; testing methods; construction practice; relative advantages of wood and metal; all-metal construction; promising steels; cost of materials. Brief abstract in Iron Age, vol. 121, no. 10, Mar. 8, 1928, p. 709.

HEAT TREATMENT. Standardization of Heat Treatment of Aeronautical Steels (La standardisation des traitements thermiques des aciers de l'aéronautique), L. Gazzaniga. *Technique Moderne (Paris)*, vol. 20, no. 5, Mar. 1, 1928, pp. 191-194.

Tables of standard treatments and examples of application; annealing of rolled, forged and machined steels; tempering and test requirements; cementation.

STEEL, AUTOMOBILE

Steel Charts to be Continued. *Soc. Automotive Engrs.—Jl.*, vol. 22, no. 3, Mar. 1928, pp. 396-398, 1 fig.

Discussion of changes proposed in physical-property charts of S. A. E. steels, or of possible advisability of discontinuing them entirely; proposal under consideration by Iron and Steel Division discussed; charts not to be changed substantially; limitation of present charts overcome; frequency curves will give accurate values; how former and proposed methods differ.

STEEL, CARBURIZED

Fatigue Tests of Carburized Steel, H. F. Moore and N. J. Alleman. *Am. Soc. Steel Treating—Trans.*, vol. 13, no. 3, Mar. 1928, pp. 405-417 and (discussion) 417-419, 12 figs.

Results of fatigue tests and of static tension tests; in general, test results suggest that carburizing, followed by suitable heat treatment, is promising means of increasing fatigue strength of steel as well as of increasing surface hardness; steel quenched in oil from carburizing pot showed more increase in fatigue strength than did steel cooled in carburizing pot.

STEEL, MILD

FLAWS. Some Defects in Mild Non-Silicon Steel (Ueber Einige Fehlererscheinungen bei der Herstellung von Weichem, Nicht Siliziertem Stahl), K. von Kerpely. *Mitteilungen des Staatl. Technischen Versuchamtes (Vienna)*, vol. 16, no. 1-3, 1927, pp. 108-117, 5 figs.

Special difficulties in manufacturing of mild steel for boilers and steam pipes; microstructure and chemistry of usual flaws.

STEEL, HEAT TREATMENT

Heat Treatment of Steel (Het uitgloeien van staal), Van Den Berg and P. Schoenmaker. *Ingenieur (Hague)*, vol. 43, no. 5, Feb. 4, 1928, pp. 51-59, 25 figs.

Reports work at metallography laboratory of Dutch ordnance office; study of microstructure of heat treated steels of various carbon contents, effect of hardening on microstructure; solidification diagrams.

STEEL, SPECIAL

Firth Sterling Circle C Steel. *Ry. Mech. Engr.*, vol. 102, no. 3, Mar. 1928, p. 176.

Steel developed in effort to produce material with considerably greater cutting capacity than standard high-speed steels; with tools made of steel under test, manganese steel can be commercially machined using cutting speeds from 7½ to 15 ft. per. min.; time of cut between grindings of tool runs from one to nine hours.
Met. Eng., vol. 35, Mar. 1928, p. 149.

News of the Society

DR. WILLIAM M. GUERTLER'S CAMPBELL LECTURE PUBLISHED

WE are glad that we are able to publish in this issue of TRANSACTIONS Dr. William M. Guertler's Edward De Mille Campbell lecture which he delivered before the eighth annual convention of the Society held in Chicago September 20 to 24, 1926. The Society, and especially the editor of TRANSACTIONS, is indebted to Dr. Samuel L. Hoyt, of the research department of the General Electric Company, Schenectady, N. Y., for his invaluable assistance in translating portions of the manuscript, obtaining and preparing illustrations and reading proofs of this paper.

Those who had the privilege of hearing Dr. Guertler when he presented this lecture, or those who heard him present it on his subsequent lecture tour of the chapters, no doubt have looked forward to the time when they could see the paper in print and thus have an opportunity of studying it in detail. His paper contains many pertinent facts and conclusions which will no doubt aid many investigators in the field of corrosion resisting materials in finding those alloys which will best meet the needs of their particular problems.

TENTATIVE RECOMMENDED PRACTICE FOR THE HEAT TREATMENT OF BLANKING DIES AND PUNCHES

THE Sub-committee on the Heat Treatment of Tool Steel of the Recommended Practice Committee of the A. S. S. T., has prepared a tentative recommended practice for the heat treatment of blanking dies and punches, which is printed below.

General—This is a tentative Recommended Practice for the Heat Treatment of Blanking Dies and Punches, and must not be applied to blanking dies and punches with a composition other than given in Table I. The steels considered in this practice are in common use for blanking dies and punches but are not the only steels used for this purpose. The heat treatments, therefore, apply only to those steels considered in this practice.

In this practice a blanking die is defined as consisting of two main parts—the stationary "die" and the moveable "punch".

Approximate Chemical Compositions—The approximate chemical compositions of the steels generally used for blanking dies are given in Table I.

Heat Treatments—The heat treatments for blanking dies and punches are given in Table II.

Notes and General Information—Usually, but not always, both the punch and die are made from the same steel. For dies of intricate design an oil hardening steel should be used but for a more simple design a water hardening steel may be used.

Table I
Approximate Chemical Composition

Steel No.	Type of Steel	Purpose	C	Mn Max.	W	Cr	V
1	Plain Carbon	Cold Work Dies and Punches	0.90-1.10	0.35	...	...	...
2	C-Va	Cold Work Dies and Punches	0.90-1.10	0.35	...	...	0.25
3	Cr-Va	Cold Work Dies and Punches	0.60-0.80	0.35	...	0.90	0.20
4[1]	Oil Hardening	Cold Work Dies and Punches	0.95	Approx. 1.15	0.50	0.50	...
5[1]	Oil Hardening	Cold Work Dies and Punches	0.90	Approx. 1.50	...	...	...
6[2]	Oil Hardening	Cold Work Dies and Punches	1.10-1.30	0.35	1.50	0.50	0.20
7	W-Cr-V	Cold Work Punches	0.50	...	2.00	1.25	0.25
8	Cr	Hot Work Dies and Punches	0.85	0.35	...	3.50	...
9	W	Hot Work Dies and Punches	0.40	0.35	10.00	3.50	0.40
10	High Speed	Hot & Cold Work Dies & Punches	0.65[3]	0.35	18.00	4.00	1.00
11[4]	High Carb High Cr	Hot & Cold Work Dies & Punches	2.25	...	...	12.00	...

[1]These steels may or may not contain vanadium.
[2]This steel may or may not contain vanadium to the approximate amount given.
[3]The carbon content for this steel may be lower for special purposes.
[4]This steel may or may not contain vanadium or cobalt.

Table II
Heat Treatments for Blanking Dies and Punches

Steel Nos. as listed in Table I	Normalizing Degrees Fahr.	Annealing[1] Degrees Fahr.	Hardening Degrees Fahr.	Hardening Quenching Medium	Tempering[2] Temperature Degrees Fahr.
1	1500-1575	1375-1425	1400-1450	Water	300- 550
2	1500-1575	1375-1425	1400-1475	Water	300- 550
3	.....	1400-1450	1425-1475	Water	350- 600
4	.....	1425-1475[3]	1450-1500	Oil	300- 550
5	.....	1375-1425[3]	1400-1475	Oil	300- 550
6	.....	1450-1500	1425-1500 1550-1625	Water[4] Oil	325- 600 325- 600
7	.....	1425-1475	1600-1675	Oil	400- 600
8	.....	1500-1550	1700-1800	Air	900-1100
9	.....	1575-1625	1850-2150[5]	Air or Oil	1000-1250
10	.....	1600-1650	2200-2325[5 6] 1950-2200[7] 1850-2100[8]	Air or Oil Air or Oil Oil	1050-1200 1050-1200 1000-1100
11	.....	1600-1650	1725-1800[9 10]	Oil	400-1000

Table II (Continued)

[1]The degree of softness depends upon the rate of cooling from the annealing temperature. Up to a certain degree of softness, the slower the cooling the softer the material.

[2]After the steel has reached the desired tempering temperature, the tempering should be continued from 30 minutes to one hour. The tempering temperatures given must necessarily cover a wide range; however, for the major portion of blanking dies and punches, the tempering temperature is towards the lower side of the range given.

[3]Steels Nos. 4 and 5 should be heated very slowly, but uniformly, to a dark red heat of approximately 1200 degrees Fahr., then raised more rapidly but uniformly to the hardening temperatures given in Table II.

[4]Oil quenching is considered preferable, but water quenching is sometimes used.

[5]These steels should be preheated at 1500-1550 degrees Fahr.

[6]Heat treatment for tools for cold work.

[7]Heat treatment for tools for hot work.

[8]Heat treatment for pack hardening. Charred sawdust or charred excelsior has been found best adapted for the packing material. Carburizing compounds should not be used. Care must be used in the use of this process that the steel does not become too highly carburized. Too high a carbon concentration on the surface will cause spalling or even an actual fusion of the surface of the die during hardening. Do not hold longer than is necessary to assure that the die has reached the desired temperature.

[9]This steel should be preheated at a temperature of 1300-1400 degrees Fahr.

[10]This steel absorbs heat slowly, so consequently should be heated much more slowly than the other steels listed. This steel is often pack hardened to prevent a soft surface resulting from decarburization. For dies which do not admit of grinding after hardening, pack hardening is recommended.

This practice will remain in tentative form for at least one year, after which it will be revised according to the comments and suggestions received from the membership.

In order that the Sub-committee on Tool Steel may be assisted in perfecting this practice, criticisms are solicited and should be directed to the secretary of the committee.

The personnel of the Tool Steel Sub-committee is as follows: J. P. Gill, Chairman; J. A. Succop, W. H. Phillips, A. D. Beeken, Jr., Joseph Taylor, C. M. Johnson, DuRay Smith, A. M Cox, Frank Garratt, and J. Edward Donnellan, Secretary, 7016 Euclid Ave., Cleveland.

Future Meetings

ANNUAL CONVENTION AND EXPOSITION—Commercial Museum, Philadelphia, October, 8-12, 1928.

SEMI-ANNUAL MEETING—Los Angeles, January 14-18, 1929.

UNAUDITED PROFIT AND LOSS STATEMENT AMERICAN SOCIETY *for* STEEL TREATING

For the period from January 1 to March 31, 1928

INCOME			
Gross Dues		$ 16,352.95	
Transactions Advertising	$ 10,982.25		
Transactions Sales	345.91		
Transactions Subscriptions	996.40	12,318.56	
Reprints		479.80	
Bindery Account		493.00	
Book Account		1,283.95	
Miscellaneous Receipts		204.28	
Data Sheets	586.65		
Data Sheet Binders	230.20	816.85	
Discounts Received	142.96		
Interest	210.04		
Premium and Discount	500.00	853.00	
Sustaining Exhibit Membership		3,150.00	
TOTAL INCOME			$ 35,952.39
EXPENSE			
Local Chapters		$ 7,030.86	
Semi-Annual Meeting—Montreal		487.07	
Transactions		9,008.88	
Reprints		383.13	
Bindery Expense		617.65	
Book Account Expense		1,004.72	
Library		56.15	
Data Sheets		877.13	
Data Sheet Binders		5.15	
Discounts Allowed		122.31	
Bank Exchange		1.32	
General Expense		2,392.50	
Collection and Legal Expense		21.14	
Insurance		470.12	
Secretary's Office		3,964.12	
Treasurer's Office		1,276.80	
Directors		1,327.64	
National Committees		2,121.86	
TOTAL EXPENSE			$ 31,168.55
EXCESS INCOME OVER EXPENSE			$ 4,783.84

BALANCE SHEET

As of March 31, 1928

ASSETS			
Commercial Account		$ 1,747.12	
Savings Account		17,375.06	
Accounts Receivable		9,965.49	
Accrued Interest		690.03	
Investments		129,000.00	
Office Furniture and Fixtures		2,879.65	
Inventory		4,535.70	
Prepaid Expense		8,287.17	
TOTAL ASSETS			$170,985.98
LIABILITIES, RESERVES AND SURPLUS			
Accounts Payable		$ 2,873.76	
Advance Receipts 1928 Convention		6,806.13	
Reserves		46,578.00	
Surplus—January 1, 1928	$109,783.79		
Plus—Credit Balance from Surplus Adjustment Account.	160.46		
Excess Income over Expense for period—January 1 to March 31, 1928	4,783.84		
Present Surplus		114,728.09	
TOTAL LIABILITIES, RESERVES AND SURPLUS.			$170,985.98

News of the Chapters

SCHEDULED MEETING NIGHTS OF CHAPTERS

For the convenience of visiting members, those chapters having scheduled meeting nights are listed below.

BOSTON—First Friday, H. E. Handy, secy., Saco-Lowell Shops, Lowell, Mass. Phone, Lowell 4050.

May 4—Stainless Iron and Stainless Steel.....V. O. Homerberg

BUFFALO—Fourth Friday. F. L. Weaver, secy., American Radiator Co., Bond Plant. Phone, Riverside 1770.

CANTON-MASSILLON—No schedule of meetings as yet received. Robt. Sergeson, secy., Central Alloy Steel Corp., Canton, Ohio. Phone 5121.

CASE GROUP—No schedule of meetings as yet received. H. E. A. Dorer, secy., Case School of Applied Science, Cleveland. Phone, Garfield 6680.

CHICAGO—Second Thursday, with exception of March 6. J. A. Comstock, secy., Room 1724 Peoples Gas Bldg. Phone, Wabash 6000, Local 364.

CINCINNATI—No schedule of meetings as yet received. N. C. Strohmenger, secy., Tool Steel Gear and Pinion Co., Elmwood Place, Cincinnati.

CLEVELAND—Third Friday. J. S. Ayling, secy., Case Hardening Service Co. Phone, Atlantic 0293.

May 18—Social Meeting.

COLUMBUS—Third Tuesday. G. D. Moessner, secy., Buckeye Steel Castings Co. Phone, Garfield 0600.

May 15—Open-Hearth Practice .....W. R. Flemming

DAYTON—No schedule of meetings as yet received. F. M. Reiter, secy., Dayton Power & Light Co.

DETROIT—Third Monday. Jos. G. Gagnon, secy., Hudson Motor Car Co. Phone, Lenox 3232.

FORT WAYNE—Paul Renfrew, secy., S. F. Bowser & Co. Phone, Harrison 2341.

May —Shop Equipment and Shop Kinks .....H. B. Northrup

GOLDEN GATE—Second Wednesday. S. R. Thurston, secy., Bethlehem Shipbuilding Corp., San Francisco.

May 9—The Hardness of Metals, Methods of Testing and What They Test. Comparison of the Wear Resistance of Different Metals Under Different Conditions of Heat Treatment.
June 13—Heat Treatments of Nonferrous Alloys, Their Purpose and Their Significance.
Moving Picture—The Story of Copper.

HARTFORD—Second Tuesday. Henry I. Moore, secy., Firth Sterling Steel Co. Phone, 6-5554 Hartford.

May 8—Manufacture of Malleable Iron.....H. A. Schwartz
June 8—Eighth Annual Banquet.

INDIANAPOLIS—Second Monday. James S. Marlowe, secy., 606 State Life Bldg. Phone, Riley 3724.

LEHIGH VALLEY—No schedule of meetings as yet received. H. V. Apgar, secy., Ingersoll-Rand Co., Phillipsburg, N. J. Phone 977.

LOS ANGELES—Second Thursday. H. V. Ruth, secy., Ducommun Corp. Phone, TR. 0621.

MILWAUKEE—Second Monday. Knight Charlton, secy., Bucyrus Co. Phone 1.

MONTREAL—No schedule of meetings as yet received. D. G. MacInnes, secy., Apt. 35, 376 Claremont Ave., Westmount, Montreal.

NEW HAVEN—Second Thursday, with the exception of June 15. F. E. Stockwell, secy., Standard Oil Co. of New York. Phone, Beacon 1520, Pioneer 9940.

May 10—Place of Nonferrous Metals in Industry.....W. G. Price and Alvan L. Davis
June —Annual Frolic—Details and date will be announced later.

NEW YORK—Second Monday. T. N. Holden, Jr., secy., E. W. Bliss Co. Phone, Sunset 9000.

NORTH-WEST—No schedule of meetings as yet received. Alexis Caswell, secy., Manufacturers' Assn. of Minneapolis.

May —Gears and Gear Steel .....E. C. Smith

NOTRE DAME—Second Friday. Frank J. Mootz, secy., Notre Dame University. Phone, Lincoln 1121.

PHILADELPHIA—Last Friday. A. W. F. Green, secy., 407 Shoemaker Rd., Elkins Park, Pa. Phone, Melrose 4542-M.

PITTSBURGH—First Thursday. H. L. Walker, secy. Box 521, North Side Station.

RHODE ISLAND—Third Wednesday. C. G. Peterson, secy., 100 Weybosset St., Providence. Phone, Gaspee 6233.

ROCHESTER—Second Monday. Irving C. Mathews, secy., Eastman Kodak Co. Phone, Glenwood 1300.

May 14—Business Meeting—Election of Officers

ROCKFORD—Second Friday. O. T. Muehlemeyer, secy., 700-702 Race St. Phone, Forest 447.

SCHENECTADY—Third Tuesday. J. G. Hicks, secy., American Locomotive Co. Phone, 2-4900-Ext 44.

SOUTHERN TIER—Third Monday. Walter H. Odgen, secy., 617 Peoples Trust Building, Binghamton, N. Y., Phone, 7754.

SPRINGFIELD—Third Monday, with exception of May 23. E. L. Woods, secy., Springfield Gas Light Co. Phone, 5-3900.

ST. LOUIS—Third Friday. C. C. Werscheid, secy., Colonial Steel Co. Phone, Garfield 1263.

SYRACUSE—Second Tuesday. S. P. Peskowitz, secy., Halcomb Steel Co. Phone, 3-1231.

TORONTO—No schedule of meetings as yet received. A. Lowry, secy., 450 Willard Ave.

TRI CITY—No schedule of meetings as yet received. George A. Uhlmeyer, secy., People's Power Co., Moline, Ill.

WASHINGTON-BALTIMORE—No schedule of meetings as yet received. H. K. Herschman, secy., Bureau of Standards.

WORCESTER—No schedule of meetings as yet received. C. G. Johnson, secy., Worcester Polytechnic Institute. Phone, P110.

STANDING OF THE CHAPTERS

DURING the month of March there were 170 new and reinstated members, while 83 were lost through arrears, resignations and deaths, leaving

a net gain for the month of 87 members. The total membership of the Society on April 1, 1928, was 5022.

Membership standing of the society as of April 1, 1928, is as follows:

GROUP I		GROUP II		GROUP III	
1. Detroit	474	1. Hartford	144	1. New Haven	87
2. Chicago	446	2. Dayton	138	2. Tri City	85
3. Pittsburgh	377	3. Los Angeles	138	3. Washington	81
4. Philadelphia	335	4. Milwaukee	120	4. Worcester	76
5. Cleveland	320	5. Golden Gate	120	5. Rockford	64
6. New York	308	6. Lehigh Valley	116	6. Columbus	60
7. Boston	267	7. Canton-Mass.	114	7. Providence	57
		8. St. Louis	106	8. Southern Tier	57
		9. Cincinnati	105	9. Rochester	53
		10. Indianapolis	94	10. Toronto	52
		11. Syracuse	85	11. Schenectady	41
		12. Montreal	74	12. Fort Wayne	41
		13. Buffalo	74	13. Springfield	39
		14. North-West	56	14. Notre Dame	31

GROUP I—Detroit with a net gain of 4 still holds first place with Chicago 28 members behind. Philadelphia and New York had a net gain of 7 each. All chapters in this group showed a gain with the exception of Chicago.

GROUP II—Hartford with a gain of 5 still maintains the lead, however, they are but 6 members ahead of Dayton and Los Angeles. Last month Los Angeles was tied with Golden Gate with 118 members for position 4, but this month Los Angeles had a net gain of 20 members, which placed them ahead of both Golden Gate and Milwaukee and brought them into a tie with Dayton for position 2.

Since January 1st, Los Angeles has made a net gain of 43 members or approximately 70 per cent. The activity of this chapter is worthy of notice and congratulations.

Golden Gate and Milwaukee are now in a tie for 4th place with 120 members each. Cincinnati advanced from 10th to 9th position passing Indianapolis; while Buffalo with an increase of 5 went into a tie for 12th place with Montreal. The following chapters made gains of 4 or over for the month; Los Angeles; Cincinnati; Hartford; Buffalo and St. Louis.

GROUP III—Since before the first of the year Tri City has held on firmly to position 1. However this month New Haven forges ahead by 2 members. Souther Tier with a net gain of 7 members advanced from 10th position to a tie with Providence for 7th place. Schenectady and Fort Wayne are tied for position 11. The following chapters in this group made gains of from 7 to 3 members: Southern Tier; Washington and Notre Dame.

BOSTON CHAPTER

The April meeting of the Boston Chapter was held at Massachusetts Institute of Technology on Friday, April 6, 1928. Dinner was served in

Walker Memorial to about sixty members of the chapter after which Mr. George Deyven, one of the local "steel pedlars" entertained with humorous stories. George has quite a reputation for story-telling around Boston and his program went over big.

The principal speaker of the evening was Professor Gordon B. Wilkes, Department of Physics at Technology, whose subject was "Pyrometry". To make a talk on pyrometers of interest to the membership as a whole is a difficult task but Prof. Wilkes had no trouble in holding the attention of his audience for more than an hour. He has been associated for many years with the division of heat measurment at M. I. T. and has had a wide experience with industrial temperature work. His talk was very practical and he covered in detail the different thermocouples and instruments in common use. He ended with a series of slides showing many installations of different types of pyrometer and heat control apparatus in various industrial plants. After the discussion a number of pyrometers, including opticals, were displayed.

Prior to the meeting, the executive committee met at Walker Memorial and nominated officers for the coming year. In the enforced absence of the chairman, the meeting was presided over by the vice-chairman, Harrison B. Parker.

H. E. Handy.

CHICAGO CHAPTER

The April meeting of the Chicago Chapter started with the usual dinner at the City Club. There were about 275 members and guests present. After dinner Chairman Barker appointed Messrs. Guthrie, Levedahl and Ford as members of the nominating committee for Chapter Officers. Following the chairman's announcements, Mr. Einar Lindeblad presented four reels of motion pictures showing the manufacture of iron and steel in Sweden. The pictures were very interesting and covered the subject in detail.

The speaker of the evening was F. R. Bonte, metallurgist of the Union Drawn Steel Company, whose subject was "Cold Finished Steel." Mr. Bonte outlined the manufacturing operations of this product and dwelt particularly on the various types of finish, structure, and sections produced, and their application for machining, cold heading and general purpose work.

At the conclusion of Mr. Bonte's paper, a very interesting discussion ensued.

A. M. Steever.

It is with regret that we note the death of L. P. Needham, district manager of Wheelock, Lovejoy, and Co., Inc., Chicago, on Friday, March 23, 1928. Mr. Needham has been an active member of the Chicago Chapter of the American Society for Steel Treating since 1919 and his absence will be keenly felt. Mr. Needham was born in Coatesville, Pa., May 24, 1890, he was graduated from Pennsylvania State College in 1915. He served in the Ordnance Department in the late war as an inspector of steels and became affiliated with Wheelock, Lovejoy and Co., in 1919. Mr. Needham was a member of many organizations. His sudden death came as a great shock to his many friends.

CLEVELAND CHAPTER

The regular meeting of the Cleveland Chapter of the American Society for Steel Treating was held Friday, March 16, in the Cleveland Engineering Society Rooms, Carnegie Hall.

The speaker, C. H. Bierbaum, vice president of the Lumen Bearing Company, Buffalo, delivered a very interesting paper on the subject of brass and bronze alloys. The talk brought out the results of years of study and research on the value of these materials for bearing purposes. The physical properties, heat treatment and its effects on these alloys as regards their use as bearing materials was ably given. The talk was supplemented by a large number of excellent slides.

A general discussion and answering of questions prolonged the interest which showed the manner in which the program was enjoyed.

Attendance at this meeting was well over 100 members and guests of which more than 40 were on hand for the dinner preceding the meeting.

J. S. Ayling.

DAYTON CHAPTER

The March meeting of the Dayton Chapter was held Wednesday evening, March 21, 1928. Forty members met at the Engineer's Club at 6:30 p. m. for a special dinner given as part of the first anniversary program of the founding of the Dayton Chapter. After the dinner the attendant members were entertained by Hal Chase of Q-Alloy fame, who gave one of his inimitable talks. Mr. Chase was permitted to choose his own subject which proved to be a discussion on "Diplomacy". The illustrations Mr. Chase chose in order to bring his ideas on diplomacy to his audience kept his hearers in a constant uproar for more than a half hour.

The regular meeting was held in the main auditorium at 8 o'clock. The illustrated educational feature "Martensite" was given by Fred M. Reiter, of the Dayton Power and Light Co.

Sixty members were present for the principal talk of the evening which was "Equipment and Methods of Heat Treatment used at Dodge Brothers, Inc.", given by H. E. Martin, assistant metallurgist of that company. The talk was illustrated by slides and motion pictures showing heat treating furnaces in operation at Dodge Brothers' plant.

The heat treating equipment used by that company is practically all electrical. The furnaces described were the large, mechanically charged, automatic, continuous and box type, normalizing and annealing furnaces, rotary carburizing furnaces for gears and electrical oil tempering baths. Mr. Martin described the design of the furnaces and the method of operation so that not only the hardness but also the structure of the treated material could be closely controlled. He gave his audience a full description of the methods used to prevent distortion and gave production data and costs in detail. The electric heat treating plant of Dodge Brothers is probably one of the most modern in the country and Dayton steel treaters were very much interested in the design and operation of this plant. A lively discussion followed the meeting.

F. T. Sisco.

HARTFORD CHAPTER

On Tuesday, March 13, the Hartford Chapter held its regular monthly meeting, with R. S. Archer, research metallurgist for the Aluminum Company of America as speaker. Mr. Archer started his talk on "Aluminum" along the historical lines and traced some of the important steps of the development of aluminum and its alloys. He then described some of the theories in the treatment of aluminum alloys, and gave a few practical examples of the applications of these theories. About one hundred and twenty-five members were present who listened to Mr. Archer's paper which took nearly two hours.

Preceding the talk on aluminum, John C. Kielman, chief engineer of the forge plant of the New Departure Company at Bristol, gave the regular monthly talk on the practical subject of "Hardening of Forging Dies". Both Mr. Kielman and Mr. Archer illustrated their talk with lantern slides.

F. G. Hughes, National President, attended the meeting and gave a short talk, amplifying some of the new changes in the National Society policies regarding data sheets and membership dues. *R. Stanton.*

NORTHWEST CHAPTER

The March meeting of the Northwest Chapter was held in the Club Rooms of the Manufacturers Association of Minneapolis, on March 20.

The chapter was indeed fortunate in obtaining O. G. Simmons, president and general manager of the National Tool Co. of Cleveland, for a lecture on gears.

Mr. Simmons discussed thoroughly the principles used in developing the evolute curve for gear teeth and illustrated with both lantern slides and moving pictures the complete historical development of gear cutters and grinders using these general principles.

It was pointed out that if tolerances of 1/10 of 1/1000 inch are to be maintained for transmission gears going into service it is necessary for metallurgists to work out modifications in the heat treatment of the available steels so that they will maintain their size after aging. So far, high speed steel is the only type that has the proper aging requirements after a specified heat treatment but these tungsten steels are too expensive for medium priced products.

At the close of this interesting meeting attended by about 60, refreshments were served in the lunch room adjoining. *R. L. Dowdell.*

NOTRE DAME GROUP

The Notre Dame Group of the American Society for Steel Treating held its regular monthly meeting in Chemistry Hall, Tuesday night, March 20.

Frank J. Mootz gave an interesting discussion entitled "Normal and Abnormal Steels" His talk was a review of all the work that has been done to date on this subject. The talk was well prepared and well received.

During the business of the meeting it was announced that the motion

picture, "The Story of Alloy Steel" had been secured and would be shown in Washington Hall, the date to be announced later.

After the business of the meeting, the members enjoyed a lunch which had been provided by the entertainment committee. *Robert E. Bannon.*

PHILADELPHIA CHAPTER

The March 30 meeting of the Philadelphia Chapter was held at the Engineers' Club, 1317 Spruce Street in Philadelphia. This meeting was attended by about one hundred and fifty members and guests and was preceded by a dinner indulged in with great relish by fifty members and friends.

The Philadelphia Chapter has been making a serious attempt to secure new members during the past eight months. The campaign has been more or less successful in that we have maintained an average membership of about three hundred and forty. An encouraging feature of the work done by the committee for obtaining memberships, has been the great number of reinstatements that have been secured. Another feature of the work has been that the type of members gotten during the past few months is such that may be counted upon to retain their membership during the coming years.

The March meeting was a strictly nonferrous type in that both speakers were chosen because of their knowledge of nonferrous metallurgy, and their ability to present subjects in an interesting way concerning their work.

The first speaker of the evening was James T. Kemp of the American Brass Company, whose subject was brass and other copper alloys. This talk, which was illustrated by lantern slides, was divided into several parts. The first had to do with the production of copper from a geographical standpoint, and the methods most commonly used for producing copper and brass. The second part of the paper dealt with the mechanical working of copper and brass, considerable detail being shown and discussed as to the rolling, drawing, extruding, etc. The final part of the paper was devoted to the metallographical studies of the copper and brass alloys.

The second speaker of the evening was Edward Searles of the Naval Aircraft Factory, Philadelphia, whose subject was Aircraft Metals. This paper was more or less of a practical type, was short and full of many interesting applications of nonferrous materials as used for aircraft constructions. *Arthur W. F. Green.*

The Philadelphia Chapter of American Society for Steel Treating has for several years sponsored a course in heat treatment and metallography of steel given in the evening school of Temple University under the direction of Horace C. Knerr, consulting metallurgical engineer. The outgrowth of this has been the formation of a society by the old students under the name of "Metallurgy Class Alumni Association of Temple University". Among the activities of this association was a visit on March 16 to the wire drawing plant of the National Umbrella Frame Company in Philadelphia, made possible by the courteous invitation of that company's management which was extended also to students of this year's course.

The company kept its plant working overtime from 5:00 to 7:00 p. m. for the benefit of the visitors, who were conducted through the plant and shown all the processes of fine wire drawing under the personal leadership of the works manager, Howard Hutchinson and his lieutenants.

After this interesting tour of inspection, the visitors were treated to a superlative dinner served in the company's new office, which temporarily had been converted into a banquet hall by professional caterers, and a thoroughly enjoyable meal was relished by all.

This great courtesy on behalf of the National Umbrella Frame Company of feeding a hungry crowd in such gorgeous style was comparable only by a most interesting paper presented by Mr. Hutchinson after the dinner.

His subject was "How to convert 800 feet of .227 dia. wire of 150,000 lbs. per square inch tensile strength and worth $4.00 per pound, into 98 miles of .0085 dia. wire of 400,000 lbs. per square inch tensile strength and worth $6,000.00 per pound".

His talk was liberally supplemented by wall charts and diagrams and was received with a hearty ovation by his listeners.

Upon parting, it was easily agreed that the evening was the finest combination of instruction, enjoyment and sociability in the life of the Alumni Association and a genuine expression of thanks was given by Mr. Knerr to Mr. Hutchinson and the management of the National Umbrella Frame Company.

C. M. Gottschau.

PITTSBURGH CHAPTER

The Pittsburgh Chapter of the American Society for Steel Treating held its regular monthly meeting at the Bureau of Mines on Thursday evening, April 5, 1928.

After dinner we were entertained by a monologist. The speaker of the evening was Dr. Zay Jeffries, National Vice-President, who gave a talk on "Hardening of Steel," illustrated by lantern slides, which was listened to with close interest by the members of the Chapter. Quite a bit of active and interesting discussion followed the presentation of Dr. Jeffries' subject.

H. L. Walker.

ROCHESTER CHAPTER

On Monday evening, March 12, the Rochester Chapter met at the Osburn Hotel for their regular meeting. Twenty-five members joined at dinner and this number was increased to forty-five at the lecture following.

The speaker of the evening was T. S. Fuller, research chemist, with the General Electric Company. Mr. Fuller chose for a subject "The Dr. Jekyl and Mr. Hyde of Metallurgy".

He assigned this title to the element hydrogen, this particular study being its capacity to penetrate steel and nonferrous metals.

As a result of tests dating back to 1912 it was found that hydrogen would penetrate ½ mm. of iron above a temperature of 225°C, the rate of penetration increasing with temperature, pressure, and elements affecting electrolysis. This rate, however, was not in direct proportion to these variables.

The apparatus used by Mr. Fuller consisted of a steel shell or tube ½ mm. in thickness, immersed in an acid bath. The inside of the tube was sealed against direct leakage. The hydrogen passing through the shell was collected at the outside of the apparatus.

Various tests led to the conclusion that hydrogen passed through the metal in its atomic or nascent state rather than a molecular state, and that it became H_2 immediately upon release at the inside surface of the shell.

Tests on the steel pieces which had been subjected to hydrogen penetration showed that they increased greatly in brittleness without apparent loss of hardness. The same phenomenon was observed in practically all classes of steel and some nonferrous metals such as copper. Microscopic analysis showed a marked separation of grain boundaries due to the internal pressure generated by occluded hydrogen.

The practical value of the developments can easily be realized, when we know that hydrogen is generated at the surface of a metal as a product of corrosion, reducing reactions, etc., and this hydrogen thus formed is a destructive element.

The lecture was followed by a lively discussion of some individual problems. The meeting closed with a rising vote of thanks to Mr. Fuller.

H. J. LeClaire.

ROCKFORD CHAPTER

The seventh regular meeting of the Rockford Chapter was held Friday, April 13 , in the Crystal Room of the Nelson Hotel. Eighty-five members and guests attended the dinner which preceded the meeting.

Chairman Swan Hillman opened the business meeting at 8 p. m. He introduced our National Secretary, Bill Eisenman, who gave a very interesting talk. He explained the new procedure for dues adopted by the National Office, and the method adopted by the National Directors for the replacement of the data sheets by an annual handbook. He urged that the members of the American Society for Steel Treating start looking ahead to the Annual Convention to be held in Philadelphia the week of October 8 and to the meeting in Los Angeles the week of January 14.

Charles Cotta, Chairman of the Nominating Committee, gave his report at this meeting for the election of officers to be held at the May meeting. Nominations were as follows:

Chairman—R. M. Smith, National Lock Company
Vice Chairman—C. C. Crain, Mattison Machine Wks.
Sec'y.-Treas.—Geo. R. Monks, % O. T. Muehlemeyer.
Directors—Alfred Lien, Ingersoll Milling Machine Co.
Harold J. Stein, Star Bit & Tool Co.
Fred Hockman, National Lock Company
Freeman G. Anderson, Mechanics Machine Co.
Duncan P. Forbes, Refined Malleable Iron Wks.

O. T. Muehlemeyer introduced the speaker of the evening, R. G. Guthrie, metallurgist of the Peoples Gas Company of Chicago. His topic was "Gas as a Tool of Industry". He spoke of the many ways in which gas is being

utilized as a tool of industry. His talk was in the form of a progress report, tracing the developments of the utilization of gas and was well illustrated with some very good slides. Considerable interesting discussion followed his talk and the meeting adjourned at 10 p. m. with a rising vote of thanks to the speakers.

H. W. Gustafson.

SPRINGFIELD CHAPTER

The March meeting of the Springfield Chapter was held Monday evening, March 26, at the Chamber of Commerce. M. J. R. Morris, metallurgist of the Central Alloy Steel Corporation, Massillon, Ohio, was the speaker, and gave the members and guests of the society a very interesting and profitable talk on alloy steels.

His subject covered a brief review of the development of iron from early days up to the present methods, the changes upon demands of materials, making for greater refinement and production of metals. Both war and peace times demand enormous tonnage of steel. The role played by the various alloying elements, chromium, nickel, vanadium, molybdenum, etc., was brought out in detail and further description was given by the use of lantern slides showing the structural differences between the physical conditions brought about by heat treatment.

An interesting discussion followed after the speaker finished his lecture. Mr. Malcolm of the Chapman Valve Co. further enlightened the audience with information regarding some of the latest trends in the alloy steel field.

T. C. Kerr.

SYRACUSE CHAPTER

The regular March meeting of the Syracuse Chapter was held on Tuesday the thirteenth, in the Chamber of Commerce Building. The meeting, of nearly 100 members and guests, was called to order by Chairman Frazer at 8:00 p. m. At the conclusion of the chapter business, F. W. Manker, vice president of the Surface Combustion Company, Toledo, Ohio, was introduced as the speaker of the evening.

Mr. Manker presented a short paper "The Advantages and Disadvantages of Oil, Gas and Electric Fired Furnaces", after which he illustrated with slides, some of the furnace set ups mentioned in the paper. From an economic standpoint, gas was described as a better fuel than oil or electricity. Oil, because of its increasingly greater domestic use, because of its being a prime requisite of the Army and Navy, and because of the greater and greater fractions being removed from the crude for automotive use, is doomed to rise in price. Because of its form factor, oil does not lend itself readily to automatic control, the most important improvement in today's heat treating furnaces. Gas and electricity are not subject to these disadvantages. Electricity, with a good form factor, is now nearly at its lowest cost, for industrial use. It is the most efficient form of heating because there are no waste products of combustion to carry away the heat.

Industrial gas has an even better form factor than either of the above fuels and is as efficient as electricity excepting the flue loss. Organizing

the gas industry for other than lighting and domestic uses, has just begun, and we have a vague idea of how cheaply this fuel may be sold in the next few years. The apparatus for gas burning is the simplest and most fool proof of the three. Short temperature gradients as well as very long ones are easily obtainable by judicious placing and controlling of burners.

S. Peskowitz.

TRI-CITY CHAPTER

The March dinner meeting of the Tri-City Chapter of the American Society for Steel Treating was held at the Davenport Chamber of Commerce, on March 21, 1928, and sixty members of the chapter listened to a splendid talk on gears by O. G. Simmons of the National Tool Company at Cleveland. Mr. Simmons' talk covered the development of the gears as we know them today, and of the machinery required to manufacture them. At the conclusion of the talk, the meeting was thrown open to an informal discussion.

George A. Uhlmeyer.

On March 8, the Tri-City Chapter of the American Society for Steel Treating lost a very valuable member in the death of C. Arthur Schoessel, of Rock Island, Illinois. Mr. Schoessel was a past officer of the Tri-City Chapter and likewise served on the Executive Committee for a number of years. Mr. Schoessel was graduated from the University of Illinois in 1913 in the department of mechanical engineering. Following his work at the University, he became associated with Deere & Company of Moline, Illinois, starting in the piece rate department. He was advanced rapidly until in June, 1923, he was made superintendent of the John Deere Harvester Plant, one of the largest plants of the Deere organization. Mr. Schoessel made a very fine superintendent and was well liked by his associates in business and outside. It is with a great deal of regret, therefore, that we have learned of his passing.

WASHINGTON-BALTIMORE CHAPTER

It is an annual custom of the Washington-Baltimore Chapter to invite one of its own members to give the address of the evening at one of the monthly meetings. On March 16, in accordance with this tradition, Jerome Strauss of the U. S. Naval Gun Factory at Washington gave a very interesting talk on aluminum bronze with special reference to the difficulties encountered in the manufacture of large ingots and castings.

The meeting had special interest not only in carrying on an old custom but also in inaugurating a new one which it is hoped may likewise become traditional. This was the first of two joint meetings to be held this year with the American Institute of Mining and Metallurgical Engineers. The second is to be held on May 11 when Dr. Mathewson will be the speaker. A banquet is to precede the talk. The date has been arranged to coincide with the annual meeting of the Metallurgical Advisory Committees to the Bureau of Standards so that many guests from outside the city are expected. A lively and interesting evening is anticipated.

WORCESTER CHAPTER

The March meeting of the Worcester Chapter was held in Rebboli's restaurant on the 14th. Mr. Bigelow, presiding, gave a brief outline of the progress made in the organization of the Worcester Engineering Society and by vote of the members present the executive committee of the local chapter was authorized to meet with committees from four other engineering societies to approve a constitution as tentatively drawn up.

R. S. Archer, metallurgical engineer of the Aluminum Company of America was introduced as the speaker of the evening. He gave a brief but comprehensive history of aluminum from its discovery in 1826 through the period of development which brought aluminum to industry on a commercial basis with the invention of a simplified process of manufacture just previous to 1890. Since that time great progress has been made through research into the effects of alloying elements and heat treatment.

Present day uses of aluminum were mentioned including electric cables, collapsible tubes, kitchen ware and washing machine parts, the latter made possible by the use of alloys to resist alkaline solutions. It is used in either the cast or wrought form for engineering purposes, castings being made in sand, in permanent molds and in die casting machines.

The most recent alloying element successfully developed is silicon, which is used to improve the non-shrinking qualities. Another recent development is the use of heat treatment to increase strength and hardness of certain aluminum alloys. The hardness may be increased in about the same proportion on the Brinnel scale as is possible with the heat treatment of tool steel. The use of aluminum paint as protective coating for aluminum or other metal parts was discussed. Aluminum paint, mixed with a suitable vehicle, deposits thin flakes of aluminum upon the surface covered.

The Worcester Chapter held its April meeting on the 5th at which the local chapters of the A. S. M. E. and the A. I. E. E. were guests. Dinner was served to sixty members and guests at Rebboli's restaurant.

Mr. Bigelow, Chairman, spoke of further progress of the Worcester Engineering Society, which is an organization composed of all the Engineering Societies located in Worcester, at the same time preserving the individuality of the different groups.

Before the speaker was introduced, a motion picture "The Mechanism of Lubrication" was shown through the courtesy of the Worcester Film Corp.

H. D. Mitchell, Chief Engineer of the Sumet Corp., of Buffalo, was introduced as the speaker of the evening, and gave a very instructive talk on bearing troubles, which he divided into a discussion of: (1) Faulty Design, (2) Improper Lubrication, (3) Incorrect Fitting, (4) Materials.

R. C. Jordan.

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